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REFERENCE

Lane, B. H., 1935, Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C. 35c.)

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GRANITIZATION, METAMORPHISM AND VOLCANISM

R. PERRIN

ABSTRACT. In Europe at least, the existence of granitization by replacement is now generally conceded, and present discussion concerns the existence of true magmatic granites, which appears to me actually to be an unnecessary hypothesis. The obvious removal of Mg and Fe in the granitization process, coupled with the absence of well-established large-scale basic fronts, strongly favors two-way diffusion in a stationary medium over circulation in a moving medium as the mechanism introducing and removing material. Following Ramberg, two-way diffusion may be attributed to minimization of the free energy of silicate structures by migration of alkalis into tectosilicates in the sial and of Mg and Fe into metasilicates in the sima. Such a diffusion theory holds promise of explaining not only granitization but also metamorphism, orogeny, and volcanism.

PRESENT STATUS OF THE GRANITE PROBLEM IN EUROPE

The conceptions of petrographers, in particular on the genesis of granites, have been altered greatly during the last twenty years; such evolution is general, but very uneven according to authors, and it has given rise to a rather too simple classification: the magmatists and the metamorphists.

What is the present state of these concepts in Europe? As a metamorphist from the onset (1934-1935) I am afraid I might be partial. I shall try, nevertheless, to give an objective outline, although this is no easy task. Works in Europe on the subject of granites are rather few and often essentially descriptive, without any reference to the genetic process; quite a few authors still seem to adopt the "wait and see" attitude, not knowing to which side the scale will tip.

I recently enquired from a colleague: "How would you sum up the opinion of European petrologists on the genesis of granites?" His reply was "I believe that, for many of them, the answer to this question depends more upon pyschoanalysis than upon logic."

I think he is right. Petrographers have long believed in magmas and magmatic differentiation alone, theories which were, in their opinion, entirely supported by experience and field study. New ideas resulting from precise observation have caused the whole question to be taken up again. The majority of authors have progressively recognized that there was some truth in those new ideas, but their boldness was somewhat disturbing. In particular, the intrusive appearance of certain granites or of dikes, which was the basis of Hutton's concepts (1785), has for a long time seemed to be an unquestionable proof of intrusion, therefore, of the liquid state of the granites.

In 1938 and 1939 our[1] statement, substantiated by evidence, that the intrusive appearance was not in itself a proof of intrusion and that replacement by metasomatism could lead to such appearances, met, we must confess, with a good deal of incredulity.

[1] To make reading easier, I shall use the word "we" every time articles written together with Roubault are mentioned.

Since then, we have cited other facts relating to granites. Along the same line, the works of Goodspeed (1940), King (1948), Phemister (1945), Higazy (1949), Misch (1949), Ramberg (1952a), and ourselves (1949c, 1952) on pegmatite and aplite dikes, have demonstrated their formation by replacement in a great many cases; as a result, the intrusive appearance is not put forward any more by certain leaders as evidence in favor of magmas; however, it would be contrary to the truth to say that some petrologists are not still impressed by this eruptive appearance. Such was still the case a few years ago when authors of metamorphist tendency, such as Read (1943, 1944), still seemed to think that the intrusive appearance was consistent with a liquid intrusion only. However, Read's metamorphism was largely based on the phenomenon of feldspathization which I used as a basis (1935) on which to reach the conclusion that the genesis of granite took place by replacement in the solid, and this commonly in the case of intrusive-looking granites.

Reynolds (1947a) and Backlund (1938), who were thorough transformists, also considered at that time, as an explanation for the intrusive appearance, a certain partial remelting after metasomatism, allowing relative displacements: this is Backlund's "rheomorphism."

The facts most in favor of a rheomorphism, at least local, seem to have been cited by Goodspeed (1952, 1953) and by Misch (1952): they are based on the presence, in some points of the rocks certainly formed by metasomatism, of euhedral crystals and of a flow structure. I do not deny the possibility of such a rheomorphism, but the facts cited do not seem to be quite conclusive evidence: 1) Feldspathization of the country rock generates "uncompleted" porphyroblasts, but also completed crystals and euhedrals, although no rheomorphism could take place in this case. 2) The flow structure resulting from an orientation of the mafic minerals often originates from a directed pressure; in the process of progressive granitization the non-existing or low changes in volume that ensue may cause directed or undirected pressures in adjacent places. There does not seem to be any other possible explanation for facts observed by us or for the inextricable mixtures granite-gneiss, the rapid succession in one granite body from non-oriented porphyroblast feldspars to oriented feldspars, etc.

In the many cases I have personally observed, the intrusive appearance of the granites seemed to find an explanation in metasomatism alone without plastic flow.

Some differences in concepts, at least partial, still seem to exist between metamorphists as regards the eruptive appearance itself.

Let us now try to proceed with psychoanalysis: for some European petrologists, the batholiths of homogeneous appearance seem to be accounted for by the liquid state phase only, replacement in the solid not being considered by them as likely to reach such a result, but this liquid state phase does not always imply in their minds differentiation and magmatic stoping. In France at any rate there is a decided tendency to come back to the old tradition of the French school: granite is the end product of metamorphism.

With respect to granites known as anatectic, containing many relicts of initial rocks, including sometimes important septa of those rocks that have

retained their initial orientation, replacement in the solid is more and more admitted; the word granitization is now quite familiar to the mind and the language. As to the difficulty of considering now a liquid state, now a solid state, according to the homogeneous or inhomogeneous nature, in cases where a batholith is homogeneous and eruptive on part of its edge and has an anatetical appearance on another part, nobody seems to have raised the question.

I shall also point out the tendency of some authors in France to consider in some cases for the granite a state that is neither solid nor liquid but semi-fluid, pasty, for instance. This is sometimes associated with the argument that under very heavy pressures there may not be any more essential differences between the liquid and the solid state. I confess that here the word solid results in confusion with the properties of glass and that it would be better to substitute the word crystalline for the word solid, as, even under very heavy pressures, there can be no confusion between the crystalline and the liquid state. This pasty state has been assumed to explain the presence in some granites of so-called displaced xenoliths because the schistosity differs sometimes from one xenolith to another—facts cited by Jung and Roques (1952) and Cogné (1950), etc. We have studied such cases, including the one observed by Cogné, and have made very peculiar observations that have caused us to find there was, in such case, no opposition between the existence of xenoliths with differing orientation of schistosity and replacement in the solid. We have published a brief note (1952) and intend to develop this problem further in the near future.

Generally, with the exception perhaps of P. Eskola (according to Erdmannsdörffer, 1950), there seem to be no more petrologists in Europe who deny the existence of granites or parts of granitic bodies formed by replacement in the solid without remelting. Even the much regretted Paul Niggli (1950), who was a great theorist and an earnest supporter of the magmatic theories, has recently classified granites in three categories: magmagranites, metagranites proceeding from metasomatism without remelting, even partial, and ultrametagranites, formed by metasomatism with at least partial remelting.

The position that there are granites and granites, stated by Read (1944), seems to correspond to the psychoanalysis of a rather large number of petrologists, a position which allows at least the "wait and see" attitude, as well as adaption to all cases. Among the leaders, only Wegmann, Reynolds, Holmes, Backlund (1943) and ourselves seem to have denied the existence of granitic magmas capable of generating granites by direct crystallization from the liquid.

In the minds of the supporters of the concept that there are granites and granites, the magmagranites are chiefly admitted for the large batholiths. Has not in fact Grout (1941) reproached the metamorphists with reaching their conclusions from studies made on the rim and over small spaces without having studied large batholiths? The studies on the large Singo batholith made by King (1947), whose conclusion was definitely in favor of metamorphism, have created a strong impression and given rise to passionate discussions in the United Kingdom. The same applied to the metamorphist conclusions of van Biljon (1949) on the Bushveld complex which, up to that

time, had been regarded as a typical demonstration of differentiation; Raguin (1949) has called attention to that study. The very interesting monograph by Misch (1949) on metasomatic granitization of Nanga Parbat and of the Sheku area does not seem to have been much studied yet on the Continent.

Generally, the supporters of "granite and granite" in Europe do not seem to take into much consideration the determination of the criteria that would allow them to distinguish the magmagranites and the metagranites, to use Niggli's terminology. This question has been raised, without any precise answer, at the Ottawa symposium. Drescher-Kaden (1948) has, however, distinguished the fabrics that would correspond, according to him, to a theoretical granitic fabric, which is distinct from the metamorphic crystalloblastic fabrics, the common occurrence of which he has found in the gneisses and granites. O. E. Erdmannsdörffer (1950) in one of the last European articles of magmatist authors on the whole granite problem, has stated objectively that this theoretical fabric was exceptional: "Die reine theorische Form allein ist kaum ja vorhanden." He has found, just as we have, in many cases, in intrusive granites, the presence of metasomatic fabrics, involving what we have called (1939) the corrosion between crystals, often called metasomatic crystalloblastic fabric. In his opinion, intrusive is evidence of liquid intrusion; therefore, to remove the objection resulting from the presence of these fabrics, he has produced a new hypothesis that he opposes to our personal concept: "Wenn echte metasomatisch Strukturen in einen geologisch als intrusiv nachgewiesenen Granit auftreten, so ist dies kein Beweis, dass diesen in seiner Gesamtheit rein metasomatisch entstanden sei." The hypothesis may be summed up as follows: after solidification and crystallization of a granite, the latter is subjected to a kind of autometamorphism in a stage called "endomagmatisch," corresponding to the end of the magmatic process; during that stage, under the influence of the supposed residual solutions, a metamorphic transformation of the granite takes place, resulting in the metamorphic crystalloblastic fabric.[2]

Observations of these crystalloblastic fabrics on granites, granodiorites, gneiss, etc., have been multiplied throughout the world. We have said that the granite fabric seemed to us characteristic of crystallization in the solid. Recently, Ramberg (1952a, p. 262) has written: "It seems apparent, on the ground of the fabric of granitic plutons, that either the large majority have recrystallized after their birth out of a melt or they originated entirely along a non-igneous path."

Very close studies of the porphyroblasts of feldspar of the gneiss, known as orthogneiss, of the Hohen Tauern in Austria, and of the relation between the porphyroblasts and the deepseated rock, have also led Exner (1948) to conclude that genesis was in the solid. He has also concluded that formation of aplite and pegmatite dikes was by replacement. The idea of orthogneiss,

[2] In fact, the metasomatic crystalloblastic fabric is more particularly pronounced along the edge as well as in the feldspathic areas isolated in the enclosing rocks. Often, more deeply inside, the feldspar crystals, for instance, seem to have cleared themselves of their inclusions, according to the illustrative expression of Misch: see also King (Singo batholith), etc. This structure corresponds, to my mind, to an uncompleted granitization and not to an autometamorphism of granite. It sets forth in evidence the progressive mechanism of granitization.

i.e. gneiss deriving from a previous magmatic rock by dynamometamorphism alone, if it has not been quite given up, tends nonetheless to become much rarer. Niggli has admitted that many gneisses, formerly regarded as ortho-, are in fact paragneisses or mischgneisses, the latter word being rather indefinite. Also augengneiss or eyed gneisses are less and less regarded as resulting from the deformation of a previous rock but as having originated directly in their present fabric.

As a matter of fact, the number of authors in Europe studying crystallization and the relationship of crystals between themselves, in order to gain some light on the genesis of rocks, seems rather limited.

I also want to call attention to a paper not yet published, from the mineralogist J. Wyart, presented at the Algiers Congress (1952); Wyart, who is not opposed to the genesis of granites by replacement but who, as a specialist in pneumatolytic mineral syntheses, believes in the predominant role of water as mineralizer, has expressed a new hypothesis: the granites would proceed from magmas consolidated in the glassy form and would then have been subjected to recrystallization in the solid under the influence of mineralizers. We have already admitted the possibility of such a process, recrystallization of rhyolites, for instance, but, in my opinion, in rare cases only; as, apart from the problem of emplacement that remains unsolved in such an hypothesis, this theory fails to explain feldspathization or the birth of isolated granitic spots in the enclosing rocks.

On the whole, the thinking of many authors on the genesis of granites results from a mixture of new and old concepts, the whole being accompanied by subjective impressions. There is at the same time fear because of the boldness of the new theories, and doubt regarding the old ones.

A question that has raised controversy, even among metamorphists, is that of the basic front of Wegmann (1935), Reynolds, Backlund (1943), etc. Erdmannsdörffer does not believe in its existence and draws an argument therefrom against the metamorphist theories, just as if such theories implied unavoidably the existence of the basic front. I do not believe in the basic front, except in very particular cases, because in all the many batholiths I have studied, particularly intrusive, there is no basic front. Such is also the opinion of Misch and of Ramberg, and the descriptions of many authors do not bring it to view.[3]

MECHANISM OF METAMORPHISM AND GRANITIZATION

If there has been a convergency of opinion, at least partial, on the genesis of granites, divergences remain very great as regards the mechanism leading to metamorphism and chiefly to migmatization and to granitization. Everyone admits the evidence of the alkaline introductions, but there is a fight between the "wet" and the "dry," to use Read's illustrative expression.

I think that the words wet and dry are in fact inaccurate. The wet are actually wet, but although I am considered as an extremist dry, I cannot say that I am unavoidably, exclusively dry.

[3] I shall base my hypotheses in connection with the mechanism of granitization on the non-existence in general of the basic front.

We have always admitted and even written that water or the OH or H ion might have played a role as catalyst in the real chemical reactions in the crystalline rocks attending granitization, reactions that are unquestionable under the microscope: there is no substitution of a crystal for another without a chemical reaction.

The essential question, to my mind, is not in fact wet or dry, but is actually the following: Is there any transport of substances by circulation of solutions or of gases, or only diffusions in a stationary medium, long distance diffusions through rocks, whether the medium in which such diffusions occur does or does not contain water in very small quantity. This is the main question for petrography, and I shall sum it up in the alternative: "circulations" or "diffusions." I am speaking, of course, of deep zones of metamorphism and granitization and not of surface zones.

Magmatists believe, of course, in "circulations," but so also do quite a number of metamorphists, in particular Read, van Biljon, (and in the U. S. A., Misch); these consider the introduction of substances as resulting from a real circulation of hot solutions or pore solutions.

My attitude as regards long distance diffusion through rocks was set forth in the booklet in which I expressed the theory of metamorphism by diffusion in the solid and I have written (1934b): "The petrographic facies presently observed on the Earth, apart from the sedimentary terrains not yet transformed, results, in its extreme variety, mainly from chemical diffusions that have occurred between the sedimentary terrains resulting from detrital or biologic actions on the elements of the first crust or on the subsequent terrains, and the deep layers, every time the temperature has been high enough for reaction speeds to be appreciable and has remained so sufficiently long enough." Along the same lines, in his fine article "Zur Deutung der Migmatite," Wegmann (1935) developed the theory of intergranular films. The two modes of diffusion have been described by us (1938c)—intergranular or lattice diffusion, with which my metallurgist training made me acquainted long ago. Since then, we have been fighting, despite the opposition we met with, in favor of long distance diffusion. Reynolds (1946) has decided in favor of diffusion of ions. Recently, in a work of very great interest and of high scientific value, Ramberg (1952a) has written: "One is forced to accept long distance diffusion through rocks as an important petrogenetic process," thus supporting my deep and persistent belief.

Ramberg is in favor of intergranular diffusion and thinks that we are "perhaps going much too far with the belief in large scale lattice diffusion" and he states in particular as argument against the importance of lattice diffusion the experiments of Jagitsch (1949). It is true that we wrote (1949a) that, while we admitted the two modes, intergranular diffusion did not seem to have played a very important part, this for reasons of geological observation. I do not believe that our knowledge in the matter of diffusion in the solid allows us presently to settle this discussion, the importance of which is indeed only theoretical; the reader whom this question might interest could refer to my paper presented at the Algiers Congress which has not yet been published, in which I answer the arguments raised against long distance

diffusion by Jagitsch which, to my mind, have no real bearing. It also cites particularly instructive experimental facts. Recently, Frederickson (1952) has expressed another hypothesis: the diffusion paths would be "channels" observed by him in micrographic examinations of a most precise nature.

But, I repeat, the discussion—lattice diffusion or intergranular diffusion —appears to me of a purely theoretical order and with no great geological bearing. If the discussion must actually be settled, it should be by geological observations. The main question, because it is full of consequences, is: circulation of hot solutions or long distance diffusion in a stationary medium.

CIRCULATION OR DIFFUSION

Ramberg (1952a) has given excellent arguments against circulation and concludes for diffusion. We have already said that the many facts of replacement known to us appear to have been initiated essentially by chemical phenomena because they have no connection with the very uneven respective solubilities of the various bodies that circulation of solutions should normally involve (unless the latter be undersaturated for all the chemical bodies in question, which hypothesis does not seem quite natural and would imply circulation of considerable volumes).

I would like to bring new arguments based again on geological observations, which remain the clue for me, in view of our still too imperfect theoretical knowledge in the field under consideration. I shall say that:

(1) Diffusion is demonstrated (in this case lattice diffusion) on the crystal scale by the phenomena of corrosion between crystals and the fact that, according to the illustrative expression of Misch, one sees, when one follows the progress of granitization, that the crystals have cleared themselves of their inclusions.

(2) On the average scale, we have already cited observations of chemical exchanges, where diffusion of components in opposite directions between different strata (our paper of 1946; Ramberg, 1952a; and other authors) or between a layer and the pebbles it contains (du Toit, J. Jung, cited by us, 1939) are evident. The diffusions in opposite directions, in "double directions," as we have called them, imply diffusion in a stationary medium and are inconsistent with a movement of hot solutions.

(3) Let us now consider migmatization and granitization. The movement of bodies by circulating hot solutions can only be envisaged if (a) either the introduction of elements such as alkalis is not accompanied by the removal of other elements such as Fe, Mg, (b) or a removal of ferromagnesians balances the introduction of alkalis, the ferromagnesians being driven in the same direction as the alkalis, i.e. outward, which involves therefore the existence of the basic front. On the contrary, if the diffusions take place in the opposite direction, alkalis outward, ferromagnesians downward, the only mechanism that may be considered is a diffusion in a stationary medium, by lattice or intergranular diffusions.

This simple reasoning shows that field observation should bring the clue to the process of granitization.

The first question is: Is there only introduction or, simultaneously, re-

moval? Without recalling here the numerous conclusions of authors in favor of a simultaneous removal, I shall follow the same deductive method I have followed to reach my conclusions on the genesis of granite—I shall start from detailed observations. It would be contrary to the scientific spirit to think that a granitic body originates from a process different from the one that is actually evidenced for the formation of a portion of that body, though small it may be, identical in composition and structure.

Let us consider feldspathization: Plate 1-A and B show two stages of evolution of xenoliths of the granite of Lanildut (Brittany) right in the heart of the batholith; the first shows a xenolith of microdiorite, rich in hornblende; in the second photograph, granitization is almost completed and the enclave scarcely differs from the granite (all the intermediate stages are to be found). It is clear from the appearance that the enrichment in K has been accompanied by a removal of Fe and Mg. Very fine examples of corrosion of hornblende and biotite by orthoclase may be seen under the microscope.[4]

The fact is still more evident in the case of the development of granitic areas isolated inside enclosing rocks, shown on plate 2-A taken at Argenton and B at Illiec Island, Brittany. The latter is particularly characteristic and conveys the impression of seeing the film of the granitization process—the edge of the granitization front reproduces the outside shape of the patches which it has joined. The chemical exchanges are written on the rocks: there has been introduction of Si and K, while at least Fe and Mg have been carried away.

I have already stated above, like other authors, that the basic front is an exceptional case. It is quite frequent to see the front of intrusive granites in gneiss or common micaschists or quartzites, etc., without any enrichment in ferromagnesians ahead of the front, whereas the study of the detail of the granitization process shows that it has been accompanied, as in the above case, by removal of Fe and Mg.

The conclusion seems quite definite; the general phenomenon of granitization or granodioritization, or migmatization, corresponds to an introduction of alkalis coming up from the depth and the return to the depth of Fe and Mg, which implies diffusions in a stationary medium.

WHAT IS THE MOTOR THAT CAUSES ALKALIS TO MOVE UPWARDS AND FERRO-MAGNESIANS DOWNWARDS?[5]

Ramberg has expressed the hypothesis of the action of the gravitation field. To explain the upward movement of the alkalis, Wegmann (1935) assumes that deepseated rocks contained alkalis and set them free. Misch (1949) has stated that it might thus be admitted that the upper part of the

[4] For simplification I have mentioned only the alkalis and the ferromagnesians, which is a general phenomenon quite easily observed, but there are actually other exchanges, in which Si, Al and Ca in particular are involved. Nor have I mentioned the question of H_2O (or OH or H), whose migration is geologically evidenced, in order not to lengthen this article. I shall only say that what may be observed seems to be accounted for if we consider water on the same basis as Na_2O, which basis gives rise to similar phenomena of diffusion.

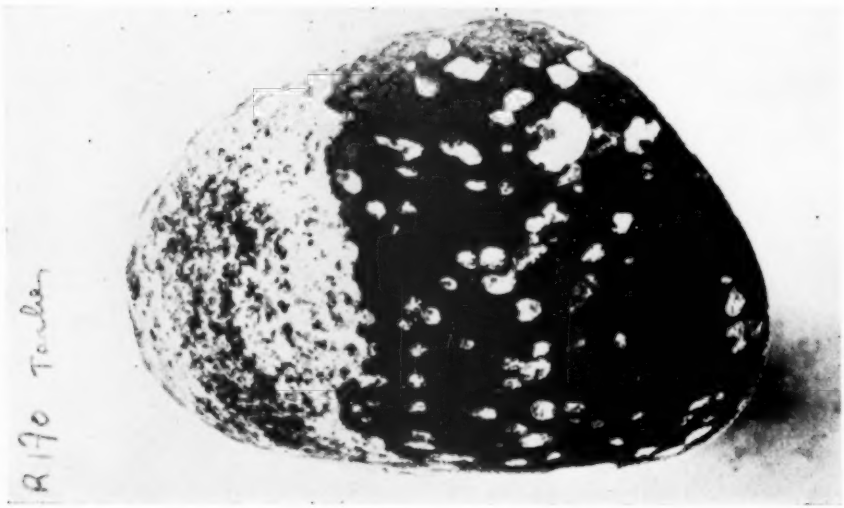
[5] This idea of motor seems to be too much neglected in the studies on diffusion speeds. There is no reason why the latter should be the same in the case of autodiffusion, of homogenization of a solid solution or of diffusion leading to decidedly exothermic re-

PLATE 1

A. Progressive feldspathization and granitization of granite enclaves of Lanildut.

B. Granitic patches isolated in a gneiss ahead of a front of granitization, Argenton (Brittany).

PLATE 2



Front of granitization, Illiec Island (Brittany). Granitic patches isolated ahead of the front: the outer form of the latter reproduces the outlines of patches.

sima is alkalinobasaltic, but he has made at the same time an objection which at first sight seems quite pertinent: the lavas that are poured out into the geosynclines prior to orogenesis, therefore prior to granitization, cannot have lost their alkalis since granitization has not yet taken place, and yet the major part thereof are not alkalic.

This objection supposes that those lavas are representative of an extrusion of a deep liquid initial sima that has remained unaltered; I shall explain below that to my mind such is not the case, which removes the objection. Ramberg is also of the opinion that metamorphism and granitization result from a tendency toward a state of equilibrium in the geosynclines. The latter have become out of equilibrium as a result of the accumulation of strata originating from the disintegration by erosion of the initial layers and of transport of materials accompanied by chemical (pH of water) and mechanical grading. These detrital strata are not in equilibrium between themselves nor with the deep strata, nor the rest of the initial crust that has not been submitted to erosion. When a rise of temperature, resulting from deep subsidence (eventually a concentration of radioactive elements) allows it, chemical diffusions begin and there is a tendency towards a new state of equilibrium by diffusion through solid rocks, in an aim toward the lowest level of free energy.

What may be the constitution of the initial crust? Geophysics teaches us that under the relatively thin layer called sial, more basic rocks called sima are to be found, but the data supplied tend more and more to show that this sima is a crystalline solid and not a liquid.

I expressed the hypothesis (1934a, b, 1948) that the constitution of the crust had been determined by a gigantic equilibrium: metal-slag-atmosphere, comparable to equilibriums that may be observed in iron metallurgy. Recent theories tend to explain the formation of the Earth by agglomeration of dust floating in the space. A verbal objection made to my theory is that the establishment of an equilibrium would have required considerable periods of time; in fact, there may not be such a wide difference between the two theories as might appear offhand to be the case. As a matter of fact, the knowledge of physical constants of bodies shows that the slag must have been liquid at a temperature when ferrous metals were still in the vapor state. Under those conditions, there would have been at first an agglomeration of the liquid particles before condensation of the metals. As their condensation proceeded, the latter would have gone through the already formed liquid slags, which is quite favorable to the quick attainment, or at least to an approach to equilibrium. In the present state of our knowledge, the most likely hypotheses are those which, being scientifically plausible, explain the maximum of known facts. I abide by my hypothesis, not because it is mine but because it explains,

actions. As an example, if we extrapolate to geologic periods of time the results of the experiments carried out by Vogel and Gibson (1950), who have measured the diffusion speed of Na ions through a plate of quartz under the influence of an electric field at 240°C., calculations made by my collaborator, J. Lamberton, show that the weight of Na carried in 10^5 years through a surface of one square meter would be of the order of approximately 10,000 tons. A real current of ions takes place in such case, and the figures computed have no longer any relation to the conclusions, very uncertain indeed, of Jagitsch.

without any added artifice, both the whole constitution of the crust, as compared with the density of the Earth, and the lack of atmosphere on the moon, and the comparison between the composition of our crust and that of the meteorites; the latter are, on the whole, decidedly richer in nickel, phosphorus and sulphur, which is quite in line with the theory of equilibrium. Finally, the consequence of such theory is that uranium, a very heavy metal, but with a strong affinity for oxygen, must have concentrated in the lithosphere.

A consequence of this theory is that the composition of the initial slag must have been very near that of a total of definite compounds,[6] and its silica content must have been of the order of 45 to 50 percent if we admit the presence of iron in the core. It is therefore not unlikely that the first layer may have contained as main constituents after cooling mixed crystals of the aluminous pyroxene and alkali pyroxene types.

Further, the external zones of metamorphism are chiefly characterized by micas such as chlorite and sericite; biotite and amphiboles or pyroxenes are to be found deeper, and last of all, the zones of gneissification, migmatization, and granitization are characterized by the progressively increasing development of feldspars, accompanied by resorption of the major part of the micas and amphiboles (I limit this enumeration to a very incomplete outline, leaving out many particular cases and many kinds of crystals, but this description is quite representative of the whole set-up as regards alkalis and ferromagnesians). In the external zones, there has been no or very low introduction of material brought from the depth; exchanges between surrounding strata have however taken place. The strong introduction of alkalis and the corresponding removal of Fe and Mg are quite apparent, principally in gneissification and migmatization.

Ramberg has shown recently (1952b) that in striving toward the lowest level of free energy, alkalis must move in the line orthosilicates → metasilicates → phyllosilicates → tectosilicates (feldspars), Fe and Mg moving in the opposite direction. The movement of alkalis indicated by Ramberg corresponds to observation.

It therefore seems to me quite natural to take advantage of Ramberg's remarks to express the hypothesis that, conversely, Fe and Mg, that are evidenced by observation to have diffused downwards, have been substituted for alkalis that might have existed at the beginning in the deep metasilicates, thus forming new metasilicates and even orthosilicates and simultaneously setting free Si. Therefore Ramberg's line of reasoning seems likely to give a general thermodynamic account for those long distance diffusions through solid rocks, provided that the original sima contained mixed silicates of Fe, Mg and alkalis, which hypothesis does not seem utterly impossible. To such action might perhaps be added that of the gravitational field of Ramberg.

When the geosynclinal condition allows diffusion, such diffusion tends to reach a new solid sima-sial equilibrium, which calls for concentration of the alkalis in the feldspars, expelling Fe and Mg from the larger part of the crystals existing in the old metamorphosed detrital strata; Fe and Mg con-

[6] The limits of this article do not allow me to state here the reasons for such assertion, which is in line with siderurgical experience.

centrate in the ortho- and metasilicates of the depth, being substituted for alkalis. On the whole, the only attempt to be made is to try and perceive the dominating features of a kind of life of the external layers of the Earth in their aim at an equilibrio-petal process; the equilibrium is never reached, were it only as a result of the resistances opposed to diffusions, of which I shall give an example below, and of the volcanic eruptions that bring back ferromagnesians into the surface zones.

In this concept, the initial external crust must have been richer in Fe and Mg than the whole of the strata (other than the lavas) that may be observed on the continents, since the latter would have become poorer in Fe and Mg. The common occurrence of large iron deposits and dolomites in the old strata does not seem to be in contradiction with this deduction. However, it is natural that the substratum of the oceans should have remained mainly basic.

VOLCANISM, METAMORPHISM, GRANITIZATION

The lavas are mainly basic, the plutonic rocks mainly acid. Numerous authors, among them Read (1943, 1944), have drawn attention to this point. However analogies in chemical composition between lavas and plutonic rocks account a great deal for the common magmatic origin which has been claimed for them. Many years ago I expressed the hypothesis that volcanoes represented magmas without roots.

Geophysical data show more and more that the crust is solid down to very great depths; hence a tendency to regard lavas as originating from the partial melting of solid rocks, following a sudden decompression brought about by fissuration of the external layers, which hypothesis is experimentally founded (Yoder, 1952).

It has often been noticed that volcanism precedes orogeny and also that a new volcanism succeeds a period of great orogeny.

Comparison of these facts leads me to outline a new theory, according to which metamorphism, granitization, and volcanism would result from one cause, namely, chemical exchanges between internal and external layers by long distance diffusion through solid rocks, only the effects of this cause being different.[7]

The tendency toward attainment of an equilibrium corresponding to the lowest level of free energy conflicts with the fact that this attainment would have as a consequence important local changes in volume. If I base myself upon the hypothesis expressed by Barth (1948a, b) that oxygen remains statically stationary in the course of diffusions owing to its extreme superabundance, I have calculated (1950) in a few cases, the analyses and densities of which I knew, the increases in volume resulting from granitization; I have found low values of the order of 2 percent. That it should be so is natural as, following Le Chatelier's principle, the difficulty of deformation of the strata of the country existing above opposes the occurrence of reactions that would involve too important changes in volume, as stated by us (1949b). Nevertheless, in relatively superficial regions, exothermic chemical reactions

[7] Ramberg (1952a, p. 273-274) also considers an acid secondary volcanism, through melting, as a consequence of orogeny, following the rise of temperature resulting from exothermy of the reactions.

resulting from diffusions may bring about changes in volume and are a cause of oregeny. Simultaneously, impoverishment in alkalis of deep metasilicates of the sial should have as a normal consequence a decrease in volume of the latter. Do we find there, apart from isostasy, a possible explanation for the sima depression and the Si-Al roots under mountain chains? (May I suggest to the readers who would question the possibility for diffusions in the solid accompanied by chemical reactions to bring about deformations that they refer to the photos published in my paper to the Algiers Congress, with the authorization of Dr. Ehlers of the University of Chicago following a very interesting test carried out by him).

If diffusions begin in depth between solid sima and subjacent detrital strata in a geosyncline under a very great thickness of the strata, deformations are not possible; exchanges tend therefore to take place without any change in volume or deformation, absorbing energy, and the exothermy of reactions considered by Ramberg brings necessarily a rise of temperature. Plastic deformations being impossible, tensions that are originated can only cause fissurations by shearing. Should such a fissuration occur, there follows a sudden decompression and, as a result, melting, at least partial, together with an increase of volume and volcanic extrusion. This extrusion stops when the excess in volume has been resorbed, and the fissure may be stopped until the cycle begins over again, unless exothermy evolved by the continuation of the reactions be sufficient to maintain the liquid column. The nature of the lavas outpoured depends upon the depth of the fissure; if it corresponds to a level of de-alkalized sima, for instance, extrusions will be basic; if, on the contrary, the fissure reaches higher layers in process of alkalization, outpourings could be rhyolitic. All compositions are possible for intermediate levels, according to the nature of the strata involved; and it is natural that compositions should undergo change, as time proceeds, for one volcano.

In the light of this hypothesis, it therefore seems normal that generally the same chemical composition should be found in the lavas and plutonic rocks since they are created by the same process of diffusion. There is however a difference, namely, that the genesis of granular rocks may be accompanied by slight increases in volume, while this does not apply to lavas, which has a bearing on possible compositions. This fact should play a part particularly in the case of acid lavas; alkali feldspars have a low concentration of oxygen (number of atoms of O per unit of volume of crystal), and their formation at the cost of other minerals tends to increase the volume, whereas quartz, on the contrary, has a relatively high concentration of O. Following this theory, during the process of formation of rocks generating rhyolites, the proportion of quartz (or tridymite) should be more important as compared with feldspars than in the granites. Is it a mere coincidence that rhyolites are actually richer in silica than granites?

According to this theory the real phenocrysts should correspond to crystals existing in solid rocks prior to remelting that have not entirely dissolved during the remelting process and removal. This would explain how, among many examples, phenocrysts of quartz known as of the first period are to be found in a mush containing quartz and feldspars known as of the second

period, which is contrary to the hypotheses of differentiation and sequences of crystallization of magmatic theories. (I have no knowledge of a magmatist explanation of these numerous aberrant facts.)[8]

Thus, outpourings of lava prior to orogeny would correspond to the beginning of diffusion in relatively deep strata. If the zone of diffusion reaches higher strata, possibilities of deformation exist, and we come to the cycle of metamorphism, granitization and orogeny. The two phenomena may, in fact, coexist during part of the passage of time. In Brittany, for instance, dark dikes of diabase may be seen cutting the granites with sharp borders, while others, on part of their course, are partly granitized with formation of eruptive breccia; others, finally, remain only as xenoliths more or less transformed or as discontinuous trails of amphibolite.

At the end of the intense period of orogenesis, the new external forms taken by the strata increase their resistance to deformation, and continuation of diffusion in depth can hardly generate anything but volcanism; the lavas will be emitted through fissures opened in the less resisting zones, therefore preferably on the edges of the Cordilleras: post-orogenic volcanism. Never in fact is the equilibrium thoroughly attained in any compartment of the crust, and volcanism may occur again by way of fissures, even in regions of old metamorphism and granitization.

Under such conceptions, volcanoes would correspond to deep chemical reaction centers, to real subjacent abscesses, unable to deform the Earth's crust, that would break through to the surface by way of fissures developed by the tensions.

Pursuing the line of reasoning I have followed for nearly twenty years I have here attempted a synthesis explaining at once metamorphism, granitization and volcanism and, partly at least, orogeny by diffusion migrations in the solid state, a consequence of the "unstable state of affairs of the geosynclinal stage," to use Ramberg's own words (1952a). He also entertains the idea of a connection between geosynclines, orogeny, granitization (Misch also), and volcanism, at least acid. I even go further and include volcanism in its entirety. Moreover, I incline to consider diffusion as one of the causes of orogenesis (other causes remain, to me, entirely mysterious), provided of course, and this seems to me likely, that such diffusions involve whole and deep compartments of the crust. Under such conception, the convection currents mentioned by Vening-Menesz and other authors in their theories on orogenesis are restricted to convections of ions.

I am under the impression that by so doing, I very much run the risk of being accused of "perhaps going much too far" and the "perhaps" may probably even be suppressed. But the thought that granitization in the solid state and long distance diffusions through solid rocks are now admitted by eminent authors is a comfort to me.

I believe, on the other hand, that when a theory leads to deductions that correspond to a non-negligible number of still unexplained geological facts and that no facts seem to be in opposition to them, one should not hesitate to

[8] The possibility of generation of phenocrysts by subsequent metamorphism of a lava should not be forgotten either. We have brought this fact to light in a precise case (1938b).

express it. Even if it is not perfect, as is certainly the case at present, or even if it is erroneous, it may cause ideas to occur to some other authors, and from these exchanges ensue advances in our knowledge.

In closing, I would like to tell of the great influence that the reading of the remarkable articles published in American publications has had upon the evolution of my own conceptions. Without excluding others, I shall mention in particular in this respect Professors T. W. Barth, L. C. Graton, G. C. Goodspeed, Peter Misch, and H. Ramberg. I wish to express to them my very deep gratitude.

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SEDIMENTARY STRUCTURES AS AN IMPORTANT FACTOR IN THE CLASSIFICATION OF SANDSTONES

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ABSTRACT. Deep water sediments deposited by turbidity currents and shallow water sediments deposited by traction currents are each characterized by a set of sedimentary structures, graded bedding being the most significant in the former and current bedding in the latter. The sedimentary structures of the two depositional types provide a basis for the division of sandstones into two suites: (1) the graywacke suite, deposited by turbidity currents, and (2) the arkose-quartzose sandstone suite deposited by traction currents. The graywacke suite includes labile graywacke, sublabile graywacke and subgraywacke; the arkose-quartzose sandstone suite includes arkose, felspathic sandstone, quartzose sandstone, labile sandstone, and sublabile sandstone. The latter two types differ from arkose and felspathic sandstone in being derived from a non-granitic terrain. Although the two suites have overlapping textural features, the typical representative of each suite is significantly different from the other. The typical graywacke suite sandstone is muddy and poorly sorted whereas the typical sandstone of the arkose-quartzose sandstone is clean and moderately well sorted.

INTRODUCTION

The many attributes of sandstone make it possible to devise a number of different classifications. Those in general use today are based entirely on mineralogical and textural characteristics. As a result there has been a good deal of disagreement about the genetic significance of certain sandstone types. The author is of the opinion that the difficulty can be largely overcome by using as a basis for classification those features which are of genetic significance, that is, features indicating the physical environment and agent of deposition. Within classes defined on the basis of these features it is possible to make a subdivision according to mineralogy or texture.

Sedimentary structures make it possible to diagnose two main agents of deposition among water-laid sandy sediments; they are traction currents and turbidity currents. Traction currents are easily observable and have consequently been known for a long time, but it is only in the past few years that the importance of turbidity currents has been appreciated, principally as a result of the work of Kuenen. Traction currents are the chief agents of deposition in neritic and non-marine environments, whereas turbidity currents are the most important agents of deposition in deep water.

FEATURES OF SHALLOW AND DEEP WATER SEDIMENTS

Since the observation of Bailey (1930) that "graded bedding and current bedding are the distinguishing marks of two different sandstone facies," many other sedimentary structures have been found to be associated more or less exclusively with current or with graded bedding. Some of these features are listed by Pettijohn (1943); those associated with graded bedding are drawn principally from his observations of Archean sediments of the Canadian Shield. The graded bedding association has also been studied by Kuenen and various associated workers, in sediments ranging in age from Cambrian to Upper Tertiary, and a list tabulating the features observed in these various sediments is given in Kuenen and Carozzi (1953). The conclusion Kuenen reached by both field observations and experimental studies is that this as-

sociation occurs in deep water and is the result of sediment deposition by turbidity currents. Table 1 lists the more important features of both shallow and deep water sediments.

The environments of deposition of these two classes of sediments can be compared with those defined by Rich (1950, 1951). His classification is based largely on macroscopic sedimentary features. The sediments with features listed in table 1 under the heading, shallow water, are ones which would be deposited in his unda-environment. The sediments classified here as deep water deposits would be laid down in Rich's clino- and fondo-environments. Unfortunately Rich underestimated the importance of turbidity currents in these latter environments; in fact, he says that coarse sediments are rare. That this is not the case, particularly in the clino-environment, has been pointed out by Kuenen (1953).

TABLE 1

Sedimentary Structures in Sediments

Shallow Water	Deep Water
One lithology often dominates.	Interbedded coarse and fine sediments, fine sediments tend to be pelagic.
Bedding tends to be lenticular and the features of the bed change over the outcrop.	Bedding regular and the beds maintain their characters over the outcrop.
Wave ripples, channel scour and coarse, often mutually opposed current bedding.	Current ripples, small scale current bedding (unidirectional). Scour absent or insignificant at the base of beds, load casting often present.
Slumps common only in current bedded units.	Slump structures, pull aparts* and slide deposits occur.
Shallow water benthos occurs in both fine and coarse beds.	Shallow water benthos absent from finer beds, reworked fossils sometimes considerably older may occur in coarser beds.
Graded bedding rare.	Graded bedding common. Finer graded beds often laminated and may show convolute bedding. Lower contacts of beds sharp, upper contacts generally so, but may grade up into pelagic beds.
Thickness of beds generally not related to grain size.	Coarser beds tend to be thicker than finer ones.

* Kuenen (1953), p. 1054.

THE GRAYWACKE PROBLEM

Apart from realizing that two distinct sandstone facies existed, Bailey (1930) considered that their sedimentary structures were important in classification. He said: "Many of the early paleozoic sandstones of Scotland and Wales are linked by three well marked characteristics. They are typically (1) muddy sandstones (2) without current bedding (3) with graded bedding. They obviously deserve a distinctive name. . . . If the original Harz greywackes show these same three characters as listed above, it would certainly be wise to retain the title greywacke and introduce into its definition a mention of the

bedding characters of the type. It may be said at once that while graded sandstones as a class are muddier than current bedded sandstones there is a well marked overlap in this respect." In a recent study by Helmbold (1952) of the Tanner graywacke (a Devonian graywacke formation of the Harz region) it is stated that graded bedding is common in the formation but does not occur in every bed. This feature is typical of all graded sandstone sequences. The Tanner graywacke is a badly sorted sandstone, as are other graywackes of the Harz region (Fischer, 1933). Thus it seems that some at least of the Harz graywackes have the features of the Scottish and Welsh graywackes described by Bailey. It is not known whether they have the other features common in sediments deposited in deep water.

It is evident that Pettijohn (1943, p. 944) is thinking of the same rock type as Bailey when he says: "Graywacke connotes a type of sandstone marked by large detrital quartz and felspar 'phenocrysts' set in a prominent to dominant clay matrix . . . and certain macroscopic structures (graded bedding, intraformational conglomerate of shale or shale chips, slip bedding etc.)." Pettijohn (1949) adds: "Cross bedding is very rare and at best is very local and on a small scale, i.e. it is restricted to layers a few inches thick."

The term graywacke has become more and more frequently used over the past twenty years, but it has not always been applied to turbidity current deposits. This is the result of the use of a number of different definitions, some of which emphasize mineral composition, others texture, and so on. For example, Krynine (1937) described the Siwalik sandstones as graywackes. They are a sequence of terrestrial sediments on the southern margin of the Himalayas. In this case the sandstones have both the texture and the mineralogy of typical graywackes, but their sedimentary structures distinguish them as shallow water traction current deposits. This is evident from what Anderson (1927, p. 679) says of them: "Throughout the system cross bedding is a notable and characteristic feature of the sandstones and to a lesser extent it may be observed in the siltstones as well."

It has been customary to think of all sandstones as belonging to a series which commences with badly sorted angular detritus containing a good deal of unstable material. As this material is transported further from the source the sorting is improved, the roundness of the grains increases, and the percentage of unstable material decreases. The final product of such a process is a pure quartz sandstone. During the process the texture of the sandstone passes through the various stages established by Folk (1951),—immature, submature, mature and supermature. The quartz index (percentage of quartz + chert divided by the percentage of all the other allogenic materials) simultaneously increases. Dapples, Krumbein, and Sloss (1953), who introduced the quartz index, found that its value ranged between 3 and 19 in the sandstones they examined. In some of the sediments studied here it reaches its possible minimum value of zero. The series described above applies only to sandstones which are deposited by traction currents, and the Siwalik sandstones are conceived as being at a point near the beginning of the series.

Graded sandstones have the characters of a texturally immature sandstone and in many cases have a low quartz index, but this does not imply

that they are an early stage in the traction current sandstones series. The textures of graded sandstones are dependent only on the fact that they are deposited from a turbidity current. Theoretically the detritus could have reached any stage of textural and chemical maturity before redeposition. The roundness of grains and the amount of unstable material present will give an indication of the previous history of transportation by traction currents. When finally deposited in deep water by turbidity currents the sediment can suffer no further transport and consequent textural modification; it is thus the end product of a process divergent from normal sandstone evolution. As a result of the overlap in textural and mineralogical features of shallow and deep water sediments, classifications depending on texture and mineralogy will group certain sandstones from each environment and hence of different origin under the same name. Such a classification is clearly an unnatural one.

If the term graywacke is to be retained for certain muddy sandstones, it is clear that it should not be used for both the Siwalik-type sandstones and graded sandstones, because of their differences in mode and environment of deposition, and consequent differences in sedimentary structures. Thus if restricted to one of them, the kind deposited by turbidity currents seems the best choice.

The problem of definition of subgraywacke also arises here. Pettijohn (1949) stated that "subgraywacke by definition contains 15 to 85 percent quartz, 0 to 10 percent felspar, 15 to 75 percent silty and clayey matrix. They usually have appreciable (5 percent) rock fragments." In other words, this definition indicates that subgraywacke is a felspar-poor variant of graywacke as defined by Pettijohn and has a similar texture. In his discussion, however, he says that subgraywacke characterizes molasse deposits. This is in accordance with his later opinion (Pettijohn, 1950) that the difference between graywacke and subgraywacke is not the percentage of felspar but the introduction of a mineral cement. Such rocks could fall almost anywhere on Pettijohn's triangular diagram; they would certainly not be confined to the subgraywacke field. Cayeux (1929, p. 166) described molasse (in the petrological sense) as follows: "Roche généralement très feldspathique, plus ou moins micacée, chloriteuse, glauconiteuse, lorsque'elle est d'origine marine, et renferment ou non des débris de roches cristallophylliennes, fréquent ou rares. . . . Gangue calcaire, ne faisant á l'argile qu'une place très négligeable et seulement notable dans une proportion très limitéchantillons." These rocks would not fall in the subgraywacke field on Pettijohn's triangular diagram; they would fall among the arkoses or graywackes depending on the degree of sorting. The sedimentary structures of the molasse sandstones indicate that they are shallow water traction-current deposits, and are hence quite unrelated to graywackes. Thus both the composition and the sedimentary structures of these sandstones suggest that the name subgraywacke should not be applied to them. The most logical usage of the term subgraywacke is to retain the original definition and to specify that the sedimentary structures and environment of deposition is the same as for graywacke.

PROPOSED CLASSIFICATION OF SANDSTONES

Sandstones of the graywacke suite.—Accepting the above argument, all graywacke-suite sandstones are deep water sediments. They occur in beds containing the structures listed under the heading "deep water" in table 1. The most important single structure is graded bedding; although it is common, it does not occur in every bed. The sorting of these sandstones is generally very poor. The percentage of matrix (as distinct from mineral cement) gives some indication of the sorting. It has been plotted against the frequency

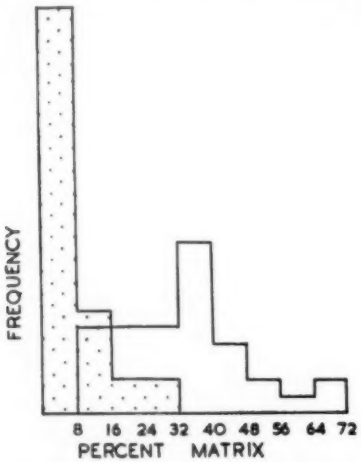

Fig. 1. Frequency of matrix percentages in sandstones studied. Stippled: Arkose-quartzose sandstone suite; unstippled: Graywacke suite.

with which it occurs in the sandstones studied (fig. 1). The range of variation is from 10 to 70 percent but there is a pronounced maximum in the interval 32 to 40 percent. The percentage of matrix is not an ideal choice for the textural study of sandstones since it gives little indication of the entire grain-size distribution. A plot of the sorting coefficient against the median diameter would be better. The ease of determination of the percentage of matrix makes it, however, the most convenient measure to use. The reason for textural variation within the graywacke suite may be related to the degree of dilution of the turbidity current depositing the sediment. This however is conjectural, and the ultimate solution of the problem will depend on the results of more experimental studies of the type described by Kuenen and Migliorini (1950).

The mineralogical variation is similarly very large. The suite shows every variation from quartz-free to quartz-rich rocks. Both the mineralogy and the texture of the sandstones studied are shown in figure 2. The mineralogical variation is a reflection of the nature of the source rocks and the transport history of the detritus previous to its deposition as a deep water sediment. The sedimentary structures and the textures are solely the result of the process of deposition. This means that Folk's terms for textural maturity are inapplicable to the graywacke suite. Certain mineralogical compositions are

more likely to occur in some tectonic environments rather than others. In eugeosynclinal regions the importance of volcanic contributions will be great, the exact mineralogy of the sediments depending on the nature of the vulcanism. The material would be derived from unconsolidated volcanic products in most cases. The graywackes of the Aure trough in New Guinea are an example of sediments in which basic volcanic material has been the principal source of detritus. As would be expected, the quartz content is small, and in some cases less than 0.1 percent is present (Edwards, 1950). The Franciscan sandstones have been derived from plutonic rocks (Taliaferro, 1943), and their association with radiolarian cherts suggests that they too are graywackes.

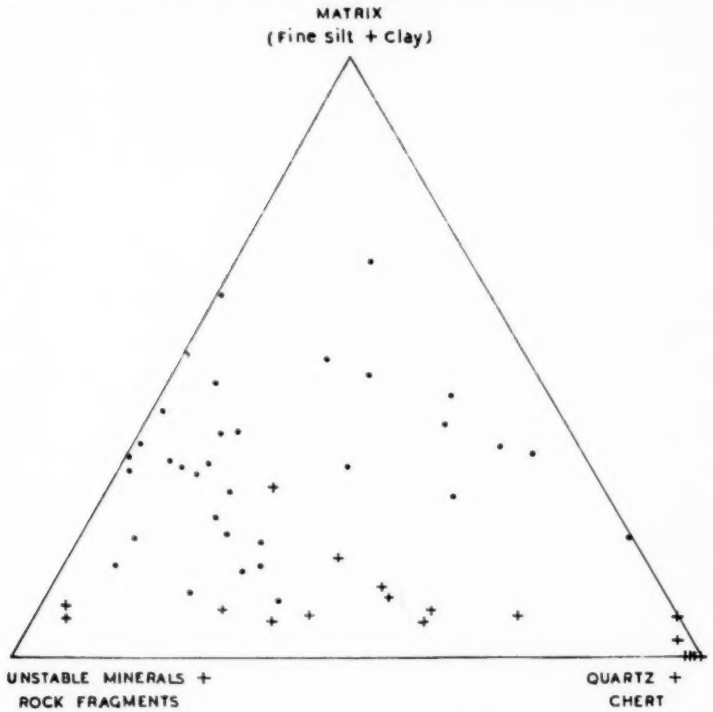

Fig. 2. Texture and mineralogy of 51 sandstones; 15 have been measured by the author, the remainder are recorded in the literature. Sandstone of the graywacke suite indicated by dot; sandstone of the arkose-quartzose sandstone suite indicated by plus sign.

They are the deep water equivalents of arkoses. Some authors have suggested oscillation of the sea floor to explain the interbedded sandstone, conglomerate, and radiolarian chert; others have disclaimed the deep water origin of the latter. The best explanation seems to be that the sediments are in fact deep water deposits and the arenaceous and rudaceous material has been brought in by turbidity currents and by sliding. The sediments containing smaller percentages of unstable material are characteristic of miogeosynclines where

vulcanism is absent and the detritus is derived from the weathering of older crystalline rocks or their sedimentary cover. Tectonism is usually less, and hence the percentage of unstable material will be substantially smaller than in a eugeosynclinal region with its large supply of unconsolidated volcanic products. Thus under these conditions subgraywackes are more probable than graywackes.

Pettijohn's graywacke-subgraywacke boundary is based on the felspar content. The definition of subgraywacke which is used here is only a minor modification of Pettijohn (1949). It is that a subgraywacke should contain less than 10 percent non-quartzose material in the rock excluding the matrix. Figure 3 shows the scheme of classification of the graywacke suite. The boundary between the fields of graywacke and subgraywacke is a line radiating from the apex (matrix) to a point on the base of the triangle representing

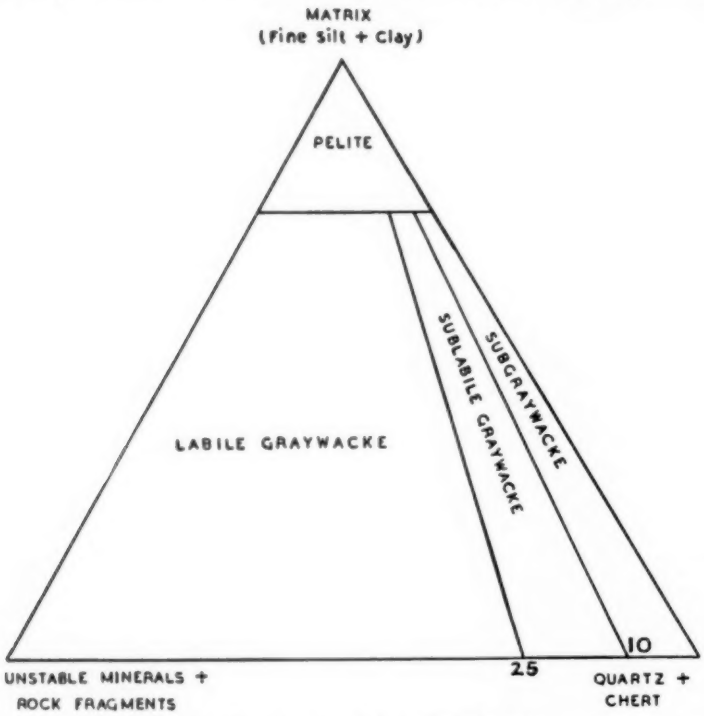

Fig. 3. Classification of the graywacke suite.

90 percent quartz plus chert. This means that the proportion of the quartzose material in the non-matrix fraction of the rock is the factor used in classification and not its absolute percentage of the entire rock.

The graywacke field has been subdivided into two parts at 25 percent unstable material in the non-matrix fraction. The graywackes with more than 25 percent unstable material are designated labile graywackes and those

with less are termed sublabile graywackes. This threefold division of the graywacke suite brings to mind the division of graywackes into quartzwackes, quartzmengwackes, mengwackes and quartz-free wackes by Fischer (1933). The boundaries of Fischer's members of the group are at 10, 33, and 90 percent unstable material respectively. His definition of the group is purely a textural one, a wacke being defined as a sandstone in which the grains are divided more or less evenly among a number of size grades. In the present paper, 10 and 25 percent unstable material in the non-matrix fraction are chosen as the boundaries between the members in order to obtain a parallelism with the classification of the sandstones of the arkose-quartzose sandstone suite.

Sandstones of the arkose-quartzose sandstone suite.—Not only the shallow water sandstones of arkosic affinity but others with widely diverse compositions have the shallow water features listed in table 1. Their sorting is indicated in figure 1; it will be seen that there is a considerable textural overlap with graywacke-suite sediments. The percentage of matrix varies from 30 percent to zero with a maximum in the region of 5 percent. Since the graywackes range from 10 to 70 percent matrix with a pronounced maximum about 35 percent, the 20 percent boundary used by Pettijohn is a good first approximation to the present classification.

If the definitions of graywacke and subgraywacke are restricted as suggested, then the only sandstone types left in the shallow water sandstone series are quartzose sandstone, felspathic sandstone and arkose, using the nomenclature of Krumbein and Sloss (1951). As arkose and felspathic sandstone are specialized types derived from granitic terrains and the names cannot be applied to sediments derived from all other possible source rocks, two analogous terms are required for sediments derived from non-granitic terrains. The use of the term molasse suggests itself, but since a good deal of confusion has arisen in its use as a facies term, a petrological usage would be ill advised. Thus it seems necessary to introduce two new terms to cover the field vacated by the restriction of graywacke and subgraywacke.

The definition of these two new types can be based on texture or mineralogical composition. Although the two are interdependent to a certain extent, their degree of freedom means that definition of one will not fix the other. For ease of determination, and more important for parallelism with the definition of graywacke and subgraywacke on one hand and arkose and felspathic sandstone on the other, mineralogical composition has been used.

The two terms proposed are labile and sublabile sandstone. A *labile sandstone* is a sandstone in which there is more than 25 percent non-quartzose material, calculated on a matrix- and mineral-cement-free basis. It also exhibits the shallow water features listed in table 1. A *sublabile sandstone* contains 10 to 25 percent non-quartzose material calculated on a matrix- and mineral-cement-free basis. The relation to other shallow water sandstones is at once apparent. Labile and sublabile sandstones may be regarded as impure arkoses and felspathic sandstones or else the latter two can be regarded as specialized types of labile and sublabile sandstones. The textural variation within one of

the defined types can be indicated by prefixing the name with one of the textural terms introduced by Folk (1951). The classification of the arkose-felspathic sandstone suite is illustrated in figure 4.

The relation between the members of the two sandstone suites is that labile graywacke is the deep water equivalent of labile sandstone and arkose, sublabile graywacke is the deep water equivalent of sublabile sandstone and felspathic sandstone, and subgraywacke is the deep water equivalent of quartzose sandstone.

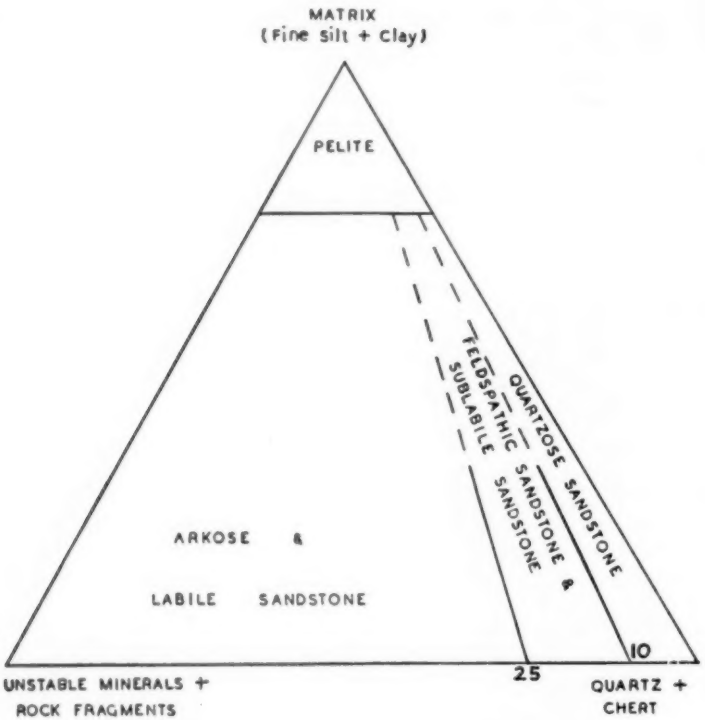

Fig. 4. Classification of the arkose-quartzose sandstone suite.

The mineralogical composition of shallow water sandstones is extremely variable, the percentage of quartzose material varying from 0 to 100 percent. The sandstones with the greatest percentage of unstable material would be expected to occur in regions where tectonic activity was strong at the time of sedimentation. The epiorogenic sediments (Glaessner and Teichert, 1947, p. 575) of the Alpine molasse are typical of these conditions. According to Kuenen and Carozzi (1953) the Alpine flysch and molasse have almost identical bulk petrographies, but the environment and agent of deposition are

TABLE 2
Classification of Sandstones

Quartzose material in non-matrix fraction	Shallow water sandstones		Deep water sandstones
	Granitic source	Non-granitic source	Granitic or non-granitic source
75%	Arkose	Labile sandstone	Labile graywacke
75-90%	Felspathic sandstone	Sublabile sandstone	Sublabile graywacke
90-100%	Quartzose sandstone	Quartzose sandstone	Subgraywacke

the factors which are responsible for their vastly different appearances. Sediments with large amounts of unstable material may also occur on unconformities or at the margins of basins of sedimentation; the unstable material in such cases is an expression not of tectonism but of proximity to the source.

CONCLUSIONS

By means of the sedimentary structures listed in table 1, it is possible to divide sandstones into types deposited in deep and shallow water. Further subdivision can be made within each class according to the percentage of unstable material in the nonmatrix fraction. This classification is summarized in table 2.

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PLASTIC DEFORMATION OF DOLOMITE ROCK AT 380°C.

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ABSTRACT. A cylinder of dolomite rock from Dover Plains, New York was compressed 9.4 percent at 380°C., 3000 atmospheres confining pressure. Deformation was plastic; but the dolomite rock is less ductile and three times as strong as Yule marble deformed under comparable conditions.

Fabric analysis shows a rather weak pattern of preferred orientation of *c* and of *a* crystal axes prior to deformation. This is somewhat modified in the deformed rock, but reorientation has not proceeded far enough to give a pattern symmetrically related to the system of applied stress. Before and after deformation the fabric is essentially homogeneous within the field of a thin section. Two mechanisms of plastic deformation have been demonstrated: (1) twin gliding on {0221}, the sense of shear being such that upper layers of the crystal lattice are displaced downwards from the upper end of the *c* axis; (2) translation gliding on {0001}, with the *a* axes as probable glide directions.

INTRODUCTION

A block of almost pure dolomite rock of lower Cambrian age, collected by Mr. G. V. Carroll from South Dover quarry, Dover Plains, New York has been selected for experimental deformation. This paper records its behavior when deformed dry at 380°C. under a confining pressure of 3000 atmospheres. Detailed analyses of the microscopic fabric before and after deformation, with special reference to preferred orientation of the component crystals, are presented; and from these certain inferences are drawn regarding the mechanism of gliding in the dolomite crystal lattice.

EXPERIMENTAL WORK

A cylinder cut normal to the *5* plane (fig. 1) was compressed 9.4 percent at 380°C., 3000 atmospheres confining pressure, dry. The apparatus, procedure, and method of reduction of the data are described elsewhere (e. g. Griggs, Turner, Borg, and Sosoka, 1953). The stress-strain curve is shown

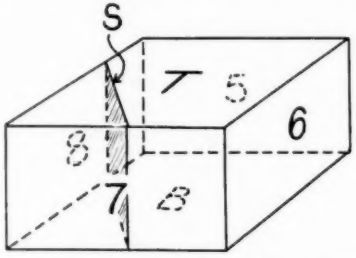

Fig. 1. Block of Dover Plains dolomite showing mutual relations of numbered faces and color-banding S.

in figure 2. When the stress began to drop, indicating the onset of shearing fracture, the load on the specimen was released. The specimen was recovered whole, with no evident macroscopic shear. The jacket was not broken. The thin section shows grain separation which suggests that intergranular cohesion was being reduced by a process of distributed shear. One other experiment on Dover Plains dolomite has been performed—a T cylinder deformed

at 300°C., 5000 atmospheres pressure. This specimen was 15 percent stronger than the 5 cylinder at 380°C. It failed by shearing fracture after 11.5 percent total strain.

These two experiments are very similar to those done by Dr. J. W. Handin at the Shell Laboratories in Houston, in which Hasmark dolomite was used. Although the Hasmark rock has quite a different fabric from that of the Dover Plains dolomite, Handin's stress-strain curves for 300°C., 5000 atmospheres are nearly identical with ours, and shearing failure occurred after about the same total strain. Our experiments were exploratory in nature, testing whether the Dover Plains dolomite had similar properties to those of the Hasmark rock.

In our experience at 300°C., 5000 atmospheres, and at 380°C., 3000 atmospheres, dolomite is not as ductile as marble and it is roughly three times as strong. Dolomite is weaker by a factor of two and is more plastic than either basalt or granite under these same conditions.

RESULTS OF PETROFABRIC ANALYSIS

Fabric of original rock.—The Dover Plains rock consists almost entirely of dolomite. Calcite is completely absent, and colorless mica and quartz are minor impurities. No foliation or lineation is visible either in hand specimen or in thin section, but there are traces of color banding (S in figure 1) normal to the T surface of the block. Grains tend to be equant and sharply bounded by nearly plane surfaces few of which, however, approximate to simple crystallographic planes. Most grains have mean diameters between 0.2 mm and 1 mm.

The optic axis of a dolomite grain is readily located by direct measurement with a universal stage,[1] so that analysis of the fabric is a much less lengthy procedure than is the case with even-grained calcite marbles where it is commonly necessary to measure a series of ordinary ray directions to locate the *c* axis of a calcite grain. Lamellae are conspicuous but rather sparsely developed (pl. 1A). They invariably are parallel to $\{02\bar{2}1\} = f$, and seldom are thick enough to allow optical identification as twinned structures. Most grains carry only one or two sets of lamellae. Characteristically they are so sharply defined that the observed angle f to c is within one or two degrees of the true value, $62\frac{1}{2}°$.

Preferred orientation of the dolomite lattice in the undeformed rock is recorded in the four orientation diagrams of figure 3. A plot of 150 *c* axes measured in three traverses across a single thin section brings out the essential pattern (fig. 3A)—a girdle within which there is a broad arc of concentration in the upper-right and lower-left quadrants. The pattern is confirmed by a diagram (fig. 3B) based on 500 *c* axes in the same section, and a high degree of homogeneity of fabric within the field of one thin section is thus established. The girdle axis is normal to T and so lies in the plane of color banding, S. The optic axes tend to be orientated at rather high angles to S.

[1] If hemispheres of refractive index 1.649 are used, no correction of tilt is necessary provided both the *c* axis and *f* lamellae are located by bringing them parallel to the E-W rotation axis of the universal stage.

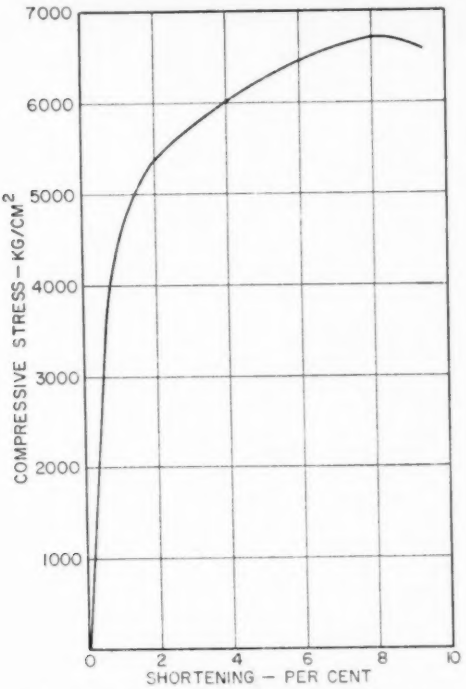

Fig. 2. Stress-strain curve for 5 cylinder of Dover Plains dolomite (specimen 403), compressed 9.4% at 380°C., 3000 atmospheres confining pressure, dry.

The three *a* axes in each of 100 grains, selected at random from those of figure 3A, were measured and plotted in figure 3C. This shows three maxima 60° apart on a great circle, suggesting some preferred orientation of *a* as well as of *c*. This is confirmed by plotting (in fig. 3D) the *a* axes of 19 grains whose *c* axes lie within 20° of the normal to the great circle containing the 3 maxima of figure 3C. In figure 3D there is marked clustering of axial points around the general *a*-axis maxima, and in 7 grains coincidence of all three *a* axes (crosses) is exact.

Figure 4E shows a plot of all conspicuous {0221} lamellae (112 lamellae measured in 100 grains). The blank central area constitutes a "blind spot" within which would lie the poles of lamellae inclined at low angles to the section and consequently inaccessible to observation. Taking this into account, there seems to be no significant pattern of preferred orientation of $\{02\bar{2}1\}$ lamellae.

Fabric of the deformed rock.—The microscopic appearance of a T section of specimen 403 (5 cylinder, shortened 9.4%) is shown in plate 1B. The most obvious result of deformation is a general increase in development of $\{02\bar{2}1\}$ lamellae which may be so abundant as to render individual grains semiopaque in ordinary light. In a number of grains coarse parting has developed approximately parallel to $\{11\bar{2}0\}$. There seems also to be a faint

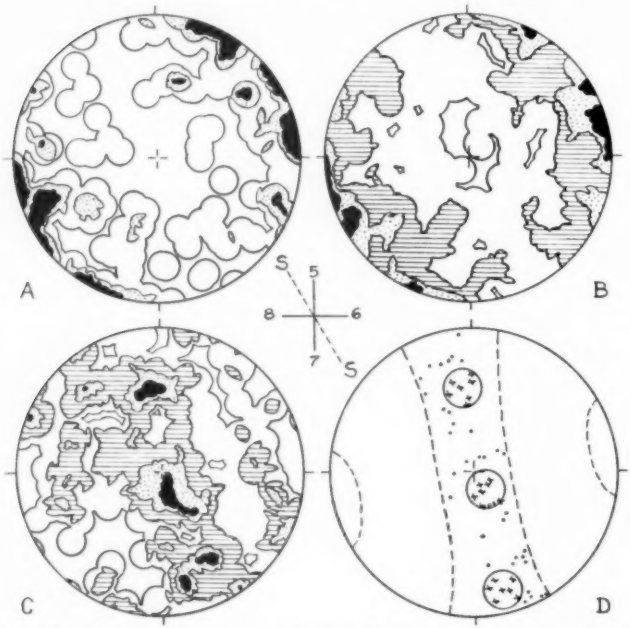

Fig. 3. Orientation diagrams, undeformed Dover Plains dolomite, T section.

A. *c* axes in 150 grains. Contours 3%, 2%, 0.7% per 1% area.

B. *c* axes in 500 grains, including those of A. Contours 3%, 2%, 1%, 0.2%, per 1% area.

C. *a* axes, 300 in 100 grains. Contours 3%, 2%, 1%, 0.3% per 1% area.

D. *a* axes in 19 grains whose *c* axes fall in the area bounded by the small circle at the east and west margins. Crosses show grains whose three *a* axes all fall within the circular areas corresponding to the maxima of diagram C.

tendency for reduction in average grain size and for slight elongation of grains parallel to the NE-SW diagonal of the photograph.

In figure 4, orientation diagrams for *c* axes (B), *a* axes (D) and conspicuous {0221} lamellae (F) are compared with corresponding diagrams (A, C, E) for the undeformed dolomite. The initial orientation pattern of the lattice has been modified in two ways: (1) the concentration of *c* axes has been condensed and displaced counterclockwise so that the mean inclination of *c* axes to the axis of compression is somewhat reduced; (2) the *a*-axis pattern of figure 4C has been partially obliterated. Neither the *c*-axis nor the *a*-axis diagram is symmetrically related to the axis of compression. A plot of 435 *c* axes (fig. 5A) brings out the state of preferred orientation of *c* axes more clearly than does the 100-grain sample shown in figure 4B.

Prominent {0221} lamellae in the deformed dolomite show almost random orientation, with a slight tendency for concentration at high rather than at low angles to the compressive force (fig. 4F).

Homogeneity of fabric.—From the close similarity between *c*-axis diagrams for 100-150 grains and for 500 grains measured in the same section,

the fabrics of the undeformed and deformed rocks appear to be essentially homogeneous within the field of a single thin section. This conclusion is confirmed by analyzing the distribution of *c*-axes of various orientations within

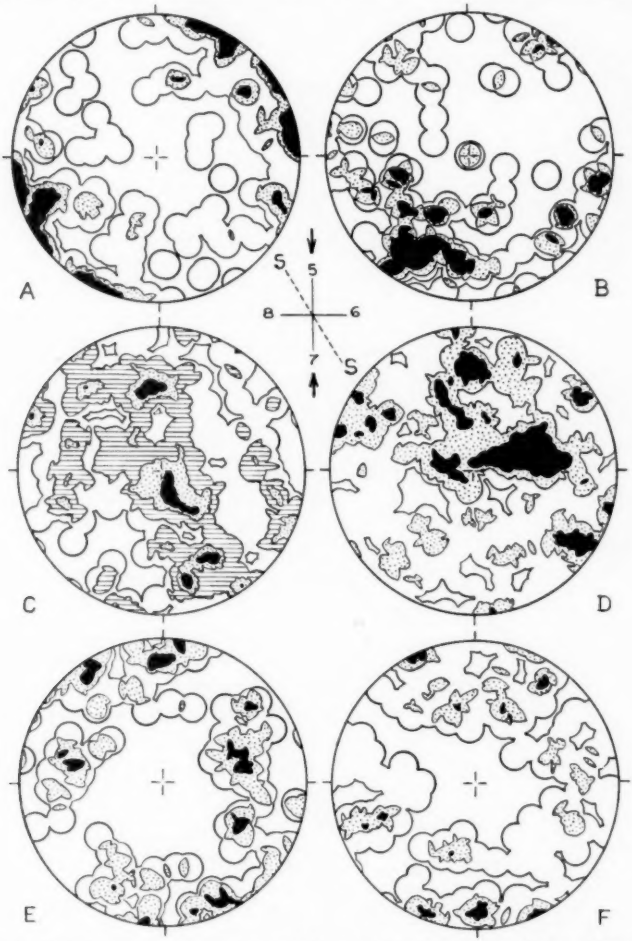

Fig. 4. Orientation diagrams for undeformed (A, C, E) and deformed Dover Plains dolomite (B, D, F). Deformed specimen (403) was shortened 9.4% in direction shown by arrows.

A. *c* axes in 150 grains. Contours 3%, 2%, 0.7% per 1% area.

B. *c* axes in 100 grains. Contours 3%, 2%, 1% per 1% area.

C, D. *a* axes, 300 in 100 grains Contours 3%, 2%, 1% (in C only), 0.3% per 1% area.

E. Conspicuous {0221} lamellae, 110 in 100 grains. Contours 4%, 2%, 1% per 1% area. Note central "blind spot."

F. Conspicuous {02$\bar{2}$1} lamellae, 142 in 100 grains. Contours 3.3%, 2%, 0.7% per 1% area. Note central "blind spot."

a particular field, according to the method described by Ramsauer (1941) and Sander (1950, p. 161-192) as *Achsenverteilungsanalyse* or *A. V. A.* The *c* axes of all grains within the area photographed in plate 1A (undeformed dolomite) are first measured. The grains are next divided into five groups according to orientation of *c* axes. Two of the orientation groups correspond to the two sectors of axial concentration in figure 3B, and the other three are arbitrarily defined. On a tracing of the photograph (pl. 1C) the grains of each group are marked by a distinctive symbol, so that any tendency for grouping of similarly oriented grains in space becomes obvious.[2] Little or no such grouping is apparent in plate 1C. In a corresponding area of the deformed dolomite (pl. 1B, D) the fabric is still essentially homogeneous except possibly for a slight tendency for similarity oriented grains to be aligned parallel to the NE-SW diagonal.

MECHANISM OF GLIDING IN DOLOMITE

Previous ideas.—Johnsen (1902) recorded experimental evidence that dolomite crystals deform plastically by gliding on $\{0001\} = c$, parallel to an *a* axis. From petrofabric analysis of natural dolomite fabrics, Fairbairn and Hawkes (1941) concluded that dolomite may also deform by twin gliding on $\{02\bar{2}1\} = f$, the sense of shear being such that upper layers of the lattice are displaced downward from the *c* axis (elsewhere we have designated this sense of movement *negative* as contrasted with *positive* sense of twin gliding on $\{01\bar{1}2\}$ in calcite). The same two mechanisms have been invoked by Bradley, Burst and Graf (1953) to explain the observed effects of progressive grinding on thermal and X-ray properties of powdered dolomite. More recently still Handin and Fairbairn (1953) have produced *f* twinning in dolomite in the laboratory at 300°C., and have confirmed the conclusion of Fairbairn and Hawkes that the sense of shear is negative.[3]

New evidence of twin gliding on $\{02\bar{2}1\}$.—In experimentally deformed Dover Plains dolomite conspicuous lamellar twinning on $\{02\bar{2}1\}$ appears in about 15 percent of the grains—usually in one, sometimes in two sets per grain. Many other grains have one or two very thin but still distinctly twinned *f* lamellae, associated with more numerous lamellae that are too thin to be optically recognized as twins. For any twin lamella the sense of shear with reference to the axis of compression is obvious. But the sense in relation to crystallographic coordinates such as the *c* axis can be determined only if it is known which of the two lattices in the grain is the original and which the newly twinned lattice. Converging evidence from four independent sources bears on this problem:

(1) In any grain with one set of lamellae there is a predominating "host lattice," and a "lamella lattice" which in aggregate makes up but a minor fraction of the total volume of the grain. Absence of half-twinned grains makes it improbable that the majority of the grains with *f* lamellae are in fact approaching a completely twinned condition. The probable alternative

[2] The critical reader is advised to color each orientation group of plate 1C and D distinctively in order better to evaluate the homogeneity of the fabric.

[3] Personal communication, November, 1953.

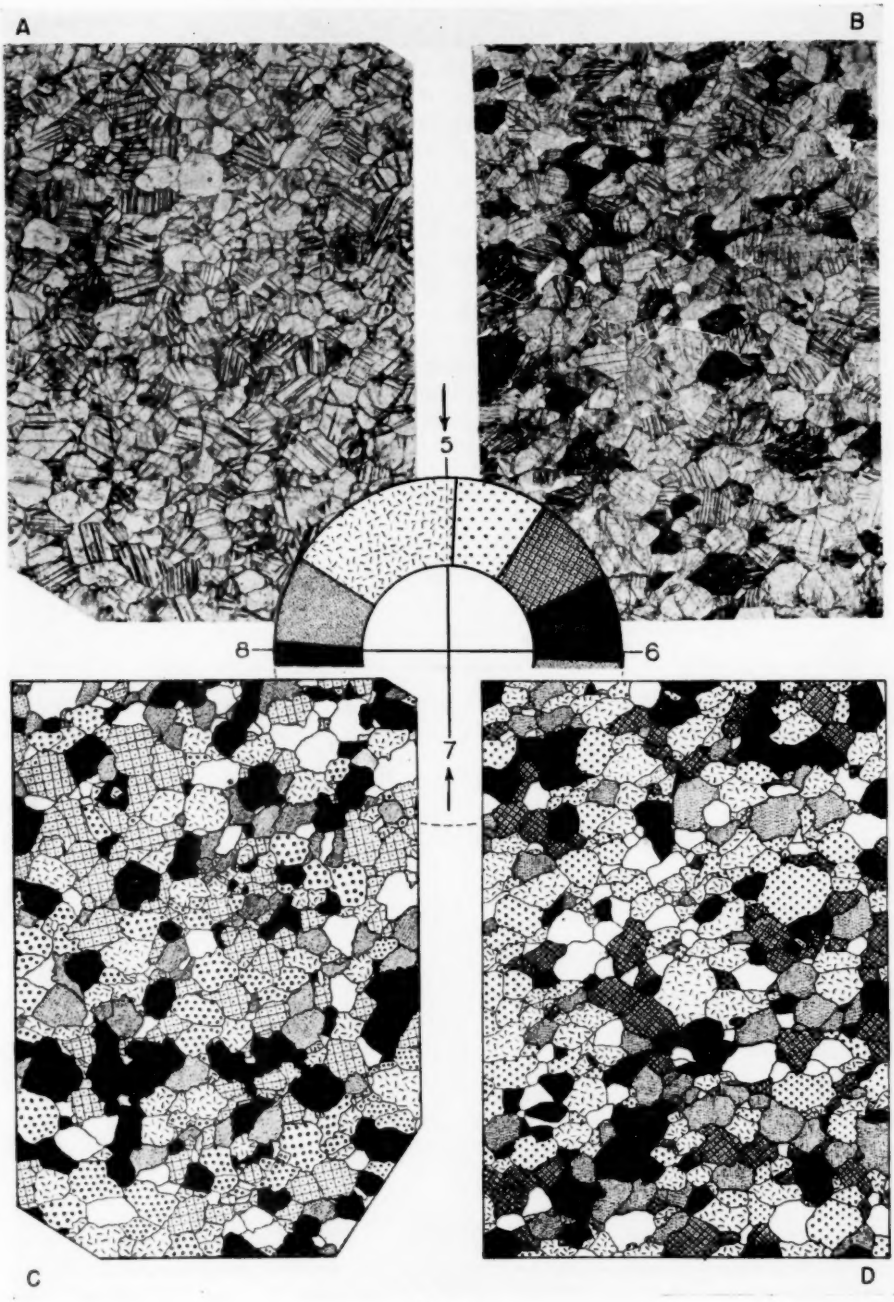

PLATE 1

Photomicrographs (X 7) of T sections of Dover Plains dolomite before deformation (A) and after deformation (B). Distribution of grains of various orientations in the photographed areas is shown in C (before deformation) and D (after deformation). Orientation of optic axes in C and D corresponds to the 6 divisions of the inset projection.

is that the host lattice is original, and the lamella lattice is the result of twin gliding.

(2) Where two sets of *f* lamellae are present in one grain, the lattice to which both *f* planes belong must be original. This is invariably the host lattice.

(3) The orientation of *c* axes in 485 grains in the deformed rock is shown in figure 5A, which combines the data of two selective diagrams: figure 5B, 407 grains in which recognizable $\{02\bar{2}1\}$ twins are absent or insignificant; and figure 5C, host lattices of 78 grains with obvious $\{02\bar{2}1\}$ twinning. The complementary nature of figures 5B and C is readily explained on the assumption that the host lattices of the twinned grains are the original lattices; for twinning would then have developed only in grains of one orientation, and almost every grain so oriented would have twinned. Moreover the observed slight reorienting of grains that are subparallel to the compression axis would be compatible with the relatively low degree of deformation of the specimen. (The percentage of grains having the *c* axis inclined at 25° or less to the compression is 12% before, and 9% after deformation.) On the other hand, two highly improbable implications arise if the host lattices of figure

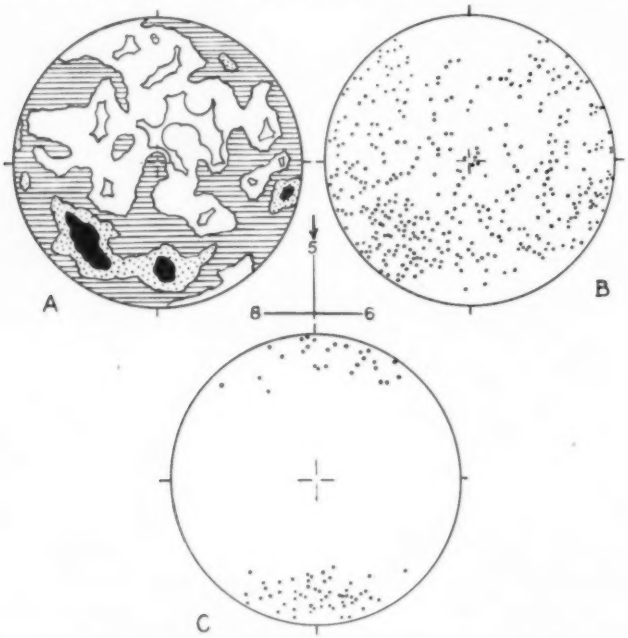

Fig. 5. Orientation diagrams for deformed Dover Plains dolomite, specimen 403 shortened 9.4% in direction of arrow.
A. *c* axes in 485 grains. Contours 3%, 2%, 1%, 0.2% per 1% area.
B. *c* axes in 407 grains showing little or no $\{02\bar{2}1\}$ twinning.
C. *c* axes in 78 grains showing obvious $\{02\bar{2}1\}$ twinning.

5C are interpreted as products of twinning: first that 78 grains whose *c* axes initially were inclined at 50°-90° to the compression axis twinned almost

completely, while many other grains of similar orientation (in fig. 5B) remained untwinned; and secondly that some 60 grains whose c axes initially were inclined at 25° or less to the compression axis have become completely reoriented by some means not involving twinning.

(4) In calcite we have found that when the lattice becomes completely twinned on an $\{01\bar{1}2\}$ plane e_1, a pre-existing lamella e_2 of different orientation rotates internally through the lattice to a new orientation L_2 that can be predicted from the geometry of twinning (Borg and Turner, 1953, p. 1349; Turner, Griggs and Heard, 1954). Similarly a pre-existing $\{02\bar{2}1\}$ lamella f_2 in dolomite will rotate internally to a new orientation during twin gliding on f_1. And this new orientation can be computed from the geometry and sense of twinning on $\{02\bar{2}1\}$. It can be shown that if shear on f_1 is negative, an original f_2 lamella rotates internally through 21° and so comes to coincide with f_2 of the twinned lattice (f'_2 in fig. 6B). If shear on f_1 were positive the angle of rotation in the opposite sense would be 28° and the

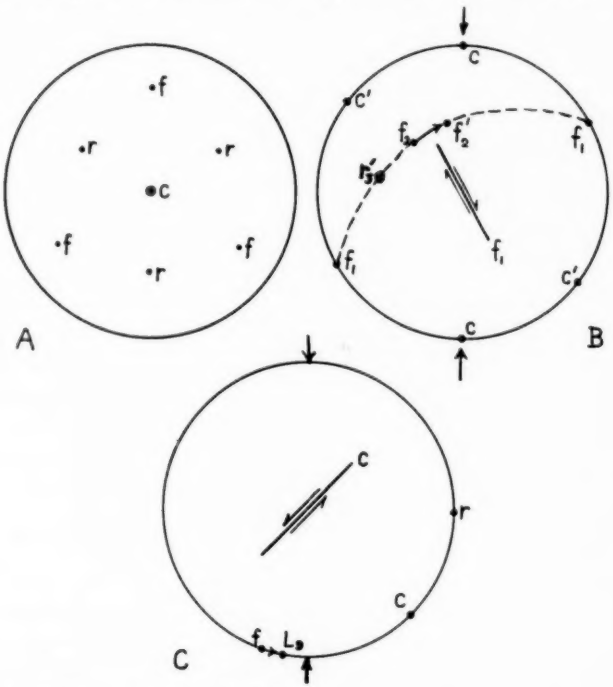

Fig. 6. Equal-area projections for dolomite.

A. Mutual relations of $\{10\bar{1}1\} = r$, $\{02\bar{2}1\} = f$, and c axis.

B. Twin gliding on f_1 induced by vertical compression. c, f_1 and f_2 are in original lattice; c', r'_3 and f'_2 are in twinned lattice. Internal rotation of f_2 to f'_2 corresponds to the sense of shear on f_1 indicated by arrows. Shear in the opposite sense would rotate f_2 to r'_3.

C. Internal rotation of f to L_2, explained by translation on $\{0001\} = c$ in the sense shown.

ultimate position of the rotated f_2 structure would coincide with r_3 of the twinned lattice (r'_3 in figure 6B). We have measured a number of dolomite grains in which an early set of f_2 twin lamellae are deflected within broad f_1 lamellae of later origin. In every instance the deflected lamela is parallel to f_2 of the lattice formed by twinning on f_1. The sense of shear on f_1 must be negative.

We conclude that the sense of shear for twinning on $\{02\bar{2}1\}$ is negative (fig. 6B), and that conspicuous twinning is restricted to grains whose c axes were originally inclined to the axis of compression at angles between zero and 25° (fig. 5C). The observed tendency for slight outward migration of c axes from the immediate vicinity of the axis of compression is attributed to external rotation of grains through a few degrees in the sense opposite to that of twin gliding.

New evidence of translation gliding.—In dolomite, as in calcite, the most satisfactory evidence of translation gliding is provided by lamellae of anomalous crystallographic orientation (Turner, Griggs and Heard, 1954). These can be identified, in dolomite, as early-formed $\{02\bar{2}1\}$ lamellae that have been internally rotated through the grain to their present anomalous orientation, in the course of translation gliding on some steeply intersecting invisible glide plane. Since the axis of internal rotation is the intersection of the glide plane and the rotated lamella, the pole of the glide plane on a projection must lie on the same great circle as the poles of the lamella, respectively before and after rotation. Choice of a glide plane is further limited by two additional requirements: the observed sense of rotation must conform to the requirements of the system of applied stress, and the coefficient of resolved shear stress, S_0, for the postulated glide system must be high. The problem, then, is to find a crystallographic glide system that satisfactorily accounts for the internal rotation of $\{02\bar{2}1\}$ lamellae in a number of differently oriented grains in a given specimen.

In the deformed specimen of Dover Plains dolomite numerous grains have a set of lamellae, which we designate L_9, intersecting rational $\{02\bar{2}1\}$ lamellae, f_1, at 6°-10°. Fortunately it is possible to locate the c axis and both f_1 and L_9 lamellae within about 1°, so that the direction and sense of internal rotation may be determined satisfactorily in most grains.

Figure 6C illustrates an ideal orientation to which most grains with L_9 lamellae closely approximate. The planes f_1, L_9, and $\{0001\} = c$ are cozonal. The pole of L_9 lies between those of f_1 and c and is 6°-10° from the pole of f_1. The pole of c is 40°-50° from the axis of compression. Gliding on c parallel to one of the a axes completely accounts for all these conditions, for S_0 has a value of 0.4-0.5, and the sense of observed rotation accords with that demanded by the orientation of c in relation to the axis of stress. No other glide system satisfies the requirements imposed by the observed data of rotation. We conclude that grains with L_9 lamellae have deformed by gliding on $\{0001\} = c$, with one of the a axes as probable glide line.

To test this conclusion, assuming translation on $\{0001\}$ parallel to a, we now compute the shortening, ε, of grains with L_9 lamellae, from the equation

$$\cot \alpha - \cot \beta = \frac{\varepsilon}{S_0} \operatorname{Sin} \gamma,$$

where α = angle L_0 to $c = 52\frac{1}{2}° - 56\frac{1}{2}°$,

β = angle f_1 to $c = 62\frac{1}{2}°$,

γ = angle a_1 (glide line) to a_2 (rotation axis) $= 60°$,

and $S_0 = 0.4 - 0.5$.

From this, ε is computed as 7%-14%, a range of values which accords with the mean of 9.4% for the specimen as a whole.

The above discussion applies to the great majority of grains with anomalous lamellae. There are a few grains, however, where the observed data of rotation are inconsistent with gliding on {0001}. It is not certain whether these rare discrepancies indicate some other mechanism of gliding or merely lack of precision in measurement. Further consideration must await future experiments in which it is hoped to achieve strains high enough to resolve such ambiguities.

CONCLUSIONS

(1) Dolomite rock compressed at 380°C. and 3000 atmospheres has been plastically deformed to give a permanent shortening of 9.4 percent. The rock is less ductile but three times as strong as Yule marble deformed under comparable conditions.

(2) One of the mechanisms of plastic deformation in dolomite is twin gliding on $\{02\bar{2}1\}$, the normal to the intersection with {0001} being the direction of gliding. The sense of shear is negative, i.e., upper layers of the lattice are displaced downward away from the *c* axis.

(3) A second and perhaps more important mechanism is translation gliding on {0001}, probably parallel to one of the three *a* axes. This leaves no trace of visible {0001} lamellae in thin sections; but it causes internal rotation of pre-existing $\{02\bar{2}1\}$ lamellae to an anomalous orientation L_0, such that the angle L_0 to {0001} is less than the angle $\{02\bar{2}1\}$ to {0001}.

(4) Shortening of a cylinder of dolomite rock by 9.4 percent leads to slight changes in the pattern of preferred orientation of the *c* axes, consistent with plastic deformation of grains by the two mechanisms just mentioned.

ACKNOWLEDGMENTS

We gratefully acknowledge financial support from the Office of Naval Research of the U. S. Navy,[4] and use of apparatus built with the assistance of grants from the Geological Society of America. We are also indebted for invaluable technical assistance to Mrs. S. Aho (preferred orientation data and drafting), and to Mr. J. de Grossé (preparation of thin sections). The difficult task of finding a suitable rock for experimental purposes was satisfactorily accomplished by Mrs. E. B. Knopf and Mr. G. V. Carroll. We owe particular thanks to Mr. Carroll who collected the experimental block from an area which he himself was mapping.

[4] Contract Nonr — 222(08), Project NR 081 134.

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OCCURRENCE, PROPERTIES, AND PARAGENESIS OF ANTHRAXOLITE IN THE MOHAWK VALLEY

JAMES R. DUNN and DONALD W. FISHER

ABSTRACT. Anthraxolite, a carbonaceous material similar to anthracite, occurs in vugs, fractures, disseminated, and within quartz crystals ("Little Falls diamonds") in the Upper Cambrian (Croixian) and Lower Ordovician (Canadian) dolomites of the Mohawk Valley, New York.

It was originally a liquid, which became concentrated in zones of relatively high porosity and permeability in a manner similar to petroleum. Having first saturated the carbonate strata, it underwent subsequent changes which produced a decrease in volume and a corresponding increase in viscosity until it attained its present solid brittle condition. These changes occurred, in part, contemporaneously with the introduction of silica and are, therefore, considered to have been brought about in the presence of an aqueous solution. The lack of recrystallization of the carbonate rocks, the absence of hydrothermal minerals, and the chemical uniformity of the anthraxolite strongly suggest that the changes were caused by ground water or non-connate sea water, rather than by juvenile fluids.

The parent material was probably vegetable and conceivably the algal reefs and biostromes of *Cryptozoon* in the Little Falls dolomite may have been the source. The end product, anthraxolite, is physically and chemically similar to anthracite. Though superficially resembling the asphaltic bitumens, it is believed to have no genetic relationship to them.

INTRODUCTION

In 1842, Vanuxem (p. 33-34) noted the occurrence of a black carbonaceous substance in the Lower Paleozoic rocks of the Mohawk Valley. He included an analysis (86.5% carbon, 11.5% water, 2% light cream-colored ash) and called the material "anthracite." Inostranzeff (1880) described similar material from the region between the White Sea and Lake Onega in the U.S.S.R. and later (1886) named it "Schungite" from the province of Shunga. The name anthraxolite was proposed by Chapman in 1888 (p. 143) for anthracite-like material occurring disseminated in sedimentary rocks. Pike (1949), in the course of his study of the quartz crystals of the Little Falls area, studied and described the carbonaceous substance but drew no conclusions as to its origin. In the course of his stratigraphic studies of the region, Fisher (1954, p. 84) noted the existence of the carbonaceous material.

Because of previous knowledge of the region, field investigation was concentrated in the Little Falls and Canajoharie areas. Except as otherwise stated, the experimental research was conducted in the laboratories of Rensselaer Polytechnic Institute. The expense of the chemical analyses, performed by Bull and Roberts, Inc. of New York City, was shared by the New York State Science Service and Rensselaer Polytechnic Institute. The authors acknowledge the loan of quartz crystals with enclosed anthraxolite from Mr. Donal Hurley of Little Falls, N. Y., and specimens in the New York State Museum which were placed at the writers' disposal.

STRATIGRAPHY

General remarks.—The anthraxolite herein discussed occurs sparingly throughout a carbonate sequence delimited below by the Precambrian basement and above by Mohawkian limestones and black shales. This interval

consists of Late Cambrian (Croixian) dolomites of varying purity and Early Ordovician (Canadian) dolomitic limestones and dolomites. A generalized composite section for the central Mohawk Valley follows:

Unit	Dominant lithology	Maximum thickness
Mohawkian		
Utica-Canajoharie	Black graptolitic shales	700 ft.
"Trenton-Black River"	Limestones	40 ft.
— — — — — — — —	—Major Break—	— — — — — — — —
Canadian		
Chuctanunda	*Cherty light gray dolomisiltite and gray-black dolomarenite. *Cryptozoon.*	40 ft.
Tribes Hill		
Fonda member	Glauconitic calcarenites and dolomite calcilutites. Very fossiliferous.	22 ft.
Wolf Hollow member	Dolomite calcilutite	28 ft.
Palatine Bridge member	Argilli-calcidolomite	55 ft.
Fort Johnson member	Dolomitic calcilutite and silty dolomisiltite	40 ft.
— — — — — — — —	—Major Break—	— — — — — — — —
Croixian (?) or Canadian (?)		
Uppermost Little Falls	*Cherty dolomarenite and dolomisiltite. Frequently red due to interstitial hematite. Vuggy. *Schizopea, Cryptozoon.*	15 ft.
	Vuggy silty dolomisiltite	30 ft.
	Feldspathic sandy dolomarenite.	5 ft.
— — — — — — — —	—Major Break—	— — — — — — — —
Croixian (?) or Canadian (?)		
Upper Little Falls	*Vuggy gray-black dolomarenite *Cryptozoon.*	45 ft.
	Thin-bedded glauconitic gray-black dolomilutite.	20 ft.
	Silty dolomisiltite and sandstone.	25 ft.
	Boulder and cobble conglomerate of chert and dolomite. (regolith?)	10 ft.
— — — — — — — —	—Major Break—	— — — — — — — —
Croixian		
Lower Little Falls	*Vuggy medium gray dolomarenite, cherty.	50 ft.
	Alternating beds of sandy and silty dolomite and coarse-grained sandstone. *Cryptozoon, Elvinia, Lingulepis.* 75 ft.	
	Breccia locally at base.	300 ft.±
— — — — — — — —	—Major Break—	— — — — — — — —
Precambrian	Granitic gneiss, garnet gneiss, augite syenite	

Note: Zones prefixed by an asterisk (*) are those which contain large amounts of anthraxolite. That anthraxolite is concentrated in four zones, each beneath a major sedimentary break, may be significant.

Little Falls dolomite.—This unit consists of dolomites, variable in color and texture, with subordinate amounts of detrital quartz, silica, feldspar, and glauconite. A basal dolomite breccia, 75 feet thick, occurs at the "Noses," 4

miles west of Fonda. Lenticular and ovoid masses of gray to brown chert up to seven feet thick occur locally. Detrital quartz increases in quantity stratigraphically downward and geographically northward. The sandstone beds exhibit well-rounded, large quartz-sand grains strongly suggesting interfingering of the isochronous Potsdam quartz-sand facies and the Little Falls carbonate facies.

The Little Falls dolomite has yielded few fossils. The lower part is of Franconian age; the co-existence of *Elvinia* establishes the synchroneity of the lower Little Falls, the Galway strata of the Saratoga region (Fisher and Hanson, 1951, p. 802), and the lower Ironton member of the Franconia formation in the type Croixian of Wisconsin. The age of the Upper Little Falls is conjectural for no fossils except *Schizopea* have thus far been discovered. A large *Lingulepis* close to *L. acuminata* has been obtained from both the basal Little Falls at the "Noses" and the Little Falls near the southern limit of the Broadalbin quadrangle. Several *Cryptozoon* biostromes exist within the Little Falls dolomite, the degree of preservation varying with the intensity of dolomitization and silicification.

The extremely barren aspect of the Little Falls, coupled with the rapid lithofacies changes, secondary silicification, and paucity of key horizon markers, makes correlation dubious between even closely adjacent sections.

Tribes Hill formation.—The carbonate unit with a prolific Gasconadian (Lower Canadian) fauna, directly overlying the Little Falls dolomite in the Mohawk Valley, was subdivided by Fisher (1954) and studied in detail.

Varied lithology is characteristic, and non-dolomitized limestones are practically non-existent in the Tribes Hill formation. Dolomitic calcilutites and silty glauconitic dolomitic calcarenites typify most outcrops. Flat pebble conglomerates are also common. Anthraxolite has not been identified with assurance in the Tribes Hill formation, though finely divided carbonaceous material is present.

The formation thins northward by offlap so that the Mohawkian limestones come to rest on the Little Falls dolomite within a few miles north of the Mohawk River.

Chuctanunda Creek dolomite.—This formation, described by Fisher (1954, p. 77, 90), is demonstrably Ordovician (Lower Canadian) because of its stratigraphic position above unquestionable Gasconadian limestones, together with its meager poorly preserved *Ophileta* and *Clarkoceras*, and accordingly is separable from the older Little Falls dolomite with which it was formerly identified.

The formation is lithologically divisible into two types of dolomite. The lower portion is dark gray-black, coarse grained and non-cherty, with considerable amounts of anthraxolite. In contrast, the upper portion is light gray, fine grained and cherty, with little or no anthraxolite. Silica has so impregnated this portion in some places that the rock behaves physically like chert. The anthraxolite in the lower portion is mainly interstitial, but vugs containing anthraxolite as coating on calcite cystals are encountered.

The Chuctanunda dolomite offlaps the Tribes Hill formation northward and westward. Except in the Amsterdam quadrangle, it has not been positively identified north of the Mohawk River. Its variable thickness is due to the post-Canadian unconformity.

OCCURRENCE AND ASSOCIATION

Anthraxolite is distributed sparingly throughout the Mohawk Valley in dolomites of Croixian and Canadian age (fig. 1). It occurs usually in partly void pockets, up to 3 inches in length, and it is also interstitially disseminated. It is found within quartz and calcite, and it cements breccias (pl. 1, fig. 2) of both chert and dolomite. Colloform masses, thin, almost spherical "bubbles" (pl. 2, fig. 1), and thin "phantom" coatings of anthraxolite (pl. 2, fig. 2) are found in quartz crystals. However, most of the anthraxolite in quartz and calcite is in the form of angular fragments which appear to have dropped on the growing crystals.

Along Flat Creek, one mile south of Sprakers (fig. 1), the anthraxolite is found filling the lower halves of horizontal elliptical pockets in a buff to reddish brown-weathering dolomite (pl. 2, fig. 4). The top halves of the pockets are filled predominantly with quartz; calcite is commonly present. The quartz and calcite crosscut the underlying anthraxolite along pronounced conchoidal shrinkage cracks (pl. 2, fig. 3). A few hemispherical pits occur in the top of the anthraxolite, and the silica has filled them so that small domical protuberances are visible on the bottom surfaces of some of the quartz.

The attitudes of 22 top surfaces of anthraxolite (18 at Flat Creek) reveal that they are tilted either south, southwest, or west, corresponding with the attitude of the fault blocks of the region. The block faulting is probably Lower Silurian. Although the tilt of the anthraxolite is fairly constant, the top surfaces are discordant with local flexures.

Pyrite is found around some of the pockets as a thin coating, particularly at Canajoharie and at the spoil bank extending westward along the south bank of the Mohawk River. At the latter locality coarse sphalerite occurs in veins with pyrite and in pockets within calcite.

PROPERTIES OF MOHAWK VALLEY ANTHRAXOLITE

Physical properties

Color	black
Hardness	2.0 (crusts at Little Falls) 3.0 (massive anthraxolite)
Luster	vitreous to dull
Fracture	conchoidal
Streak	black
Specific gravity	1.32-1.41
Fusibility	infusible
Crystal form	amorphous
Structure	botryoidal, massive, crustiform

Chemical properties

1. Insoluble in carbon tetrachloride, benzene, acetone, toluene, ethyl ether, methyl alcohol, diethylene glycol, petroleum ether, dioxane, ethanolamine, and carbon disulfide.

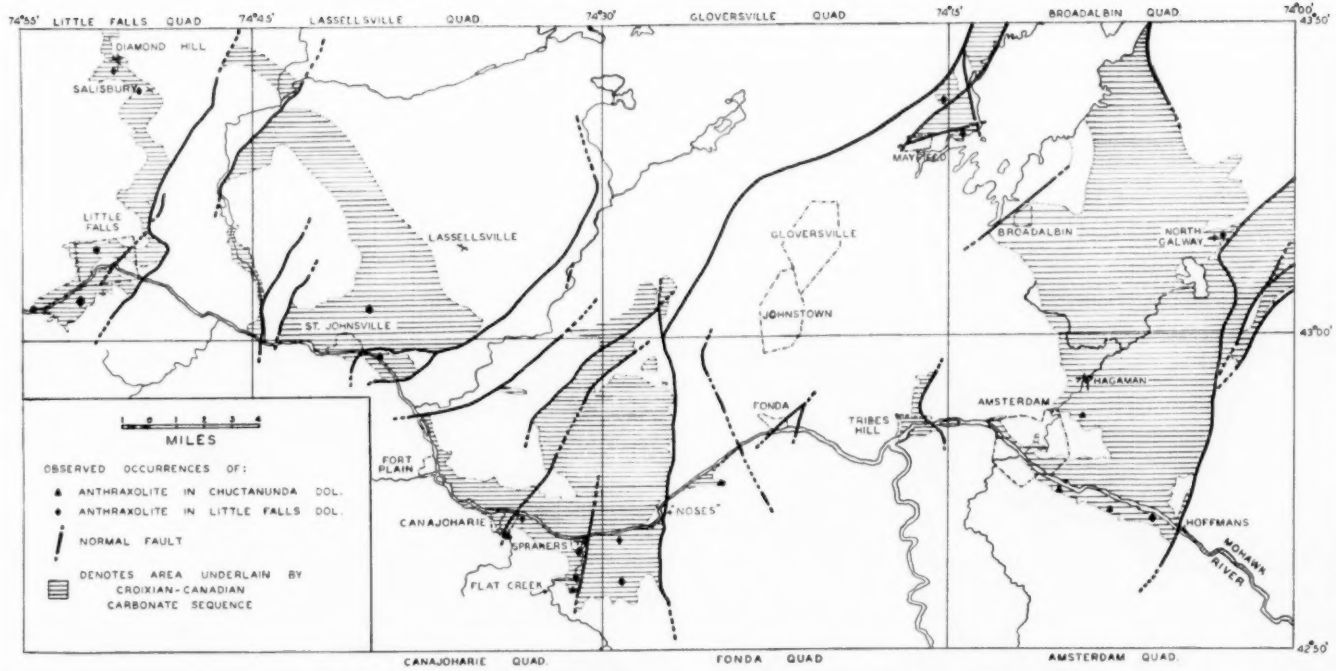


Fig. 1. Geologic sketch map of a portion of the Mohawk Valley showing distribution of Croixian and Canadian strata and occurrences of anthraxolite.

PLATE 1

1

2

Fig. 1. Vuggy dolomite showing cavities lined with anthraxolite. A free quartz crystal occurs in one of the vugs.

Fig. 2. Brecciated dolomite with anthraxolite filling the fractures.

PLATE 2

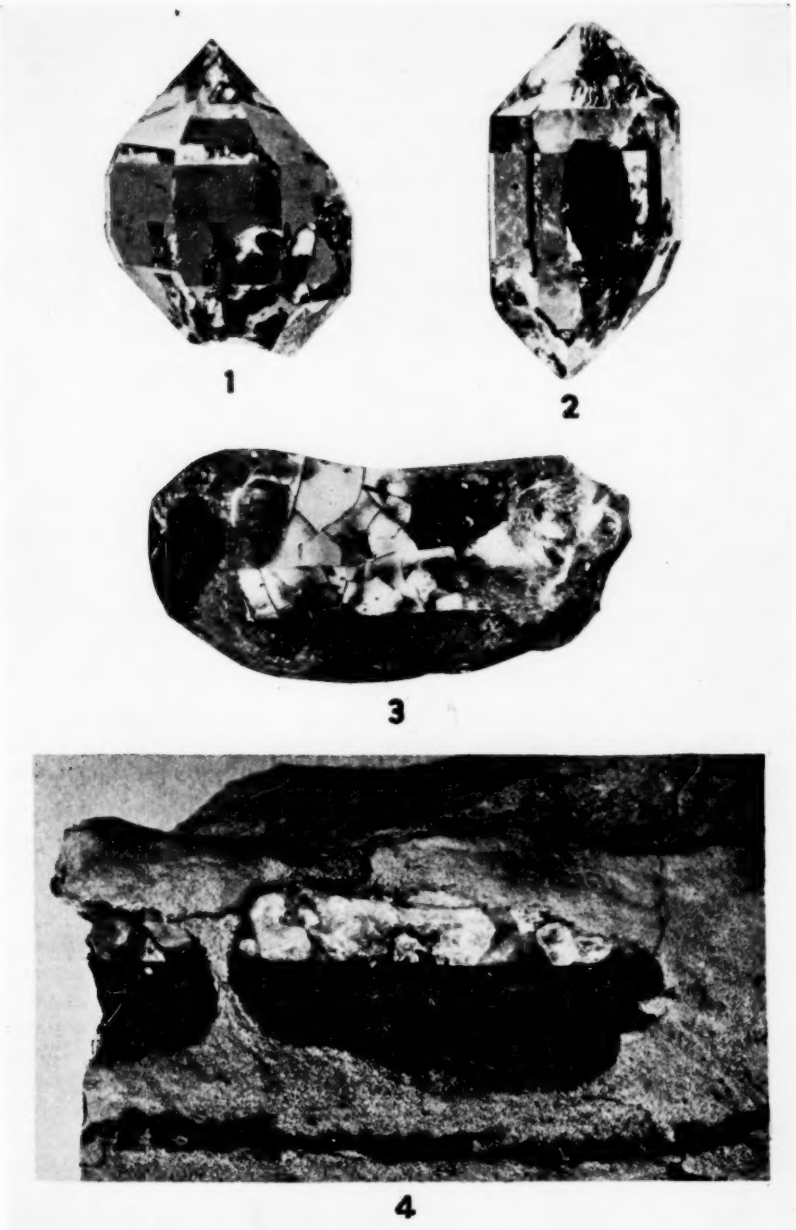


Fig. 1. Quartz crystals including a spherical film of anthraxolite. (X2)

Fig. 2. Quartz crystal containing "phantom" coated with anthraxolite and encased by later quartz. (X 2.5)

Fig. 3. Shrinkage phenomena on surface of contact of quartz and anthraxolite from a cavity filling. Some of the underlying anthraxolite adheres to the quartz. (X 1.5)

Fig. 4. Profile of vug from uppermost Little Falls dolomite showing the relative positions of the quartz (above) and anthraxolite (below). A curved veinlet of quartz cuts the anthraxolite. (X 1.5)

2. Decomposed by concentrated sulfuric acid.
3. Spectroscopic analysis of anthraxolite from Flat Creek showed no lines which could not be explained as impurities in the carbon electrodes.
4. Volatile content in closed tube, 7% to 8% (8 samples).
5. Most of the anthraxolite was unaltered when heated in the closed tube. In some samples, however, a few grains were altered to coke.
6. A "petroliferous" odor is emitted when material from the spoil bank at Little Falls is pulverized.

Ultimate Analyses of Some Anthraxolites and Related Substances

	1	2	3	4	5	6
C	90.42	90.50	90.25	94.92	98.11	93.50
H	3.94	3.97	4.16	0.52	0.43	2.81
O	3.42	1.93	3.69	1.69	—	2.72
N	1.30	1.36	0.52	1.04	0.43	0.97
S	0.57	0.52	0.66	0.31	—	—
Ash	0.35	1.72	0.72	1.52	1.09	—
	100.00	100.00	100.00	100.00	100.06	100.00
Specific Gravity	1.37	1.39	1.37	1.87	1.84	1.65

1. Anthraxolite, uppermost Little Falls dolomite, Flat Creek near Sprakers, N. Y. Analysis by Bull and Roberts, Inc., 1953.
2. Anthraxolite, Little Falls dolomite, abandoned quarry at Salisbury, N. Y. Analysis by Bull and Roberts, Inc., 1953.
3. Anthraxolite, within a vein of barite in the Black River limestone near Kingston, Ontario. Analysis by W. H. Ellis (1897, p. 163).
4. Anthraxolite, Cambrian near Sudbury, Ontario. Analysis by W. H. Ellis (1897, p. 163).
5. Schungite, "Huronian" from Olenets province (between Lake Onega and the White Sea), U.S.S.R. Average of 4 analyses by A. Inostranzeff, 1880.
6. Anthracite coal, average of 16 analyses of anthracites from various places. F. W. Clarke (1920, p. 761).

Discussion of the properties.—The physical properties of the massive anthraxolite are remarkably constant and seemingly do not vary appreciably with areal or stratigraphic position. The specific gravity, as determined with the Berman Balance, was found to range from 1.32 to 1.41 for 31 samples: 16 of the results were in the 1.38 to 1.40 range. All the massive material possessed a hardness of 3.0. Most of the anthraxolite has a rather dull luster. An exception is some lustrous material from the abandoned quarry at the eastern edge of Canajoharie. It is noteworthy that the only lustrous anthraxolite encountered was from an actively working quarry. This suggests that exposure to air may have produced the dull luster.

The disseminated anthraxolite at Diamond Hill, 2 miles northwest of Salisbury, and the thin botryoidal crusts lining the pockets at the spoil bank at Little Falls differ physically from the massive materials. The crustiform anthraxolite from Little Falls, with a hardness of 2.0, is the material which emits a petroliferous odor when scratched. Nevertheless, massive anthraxolite

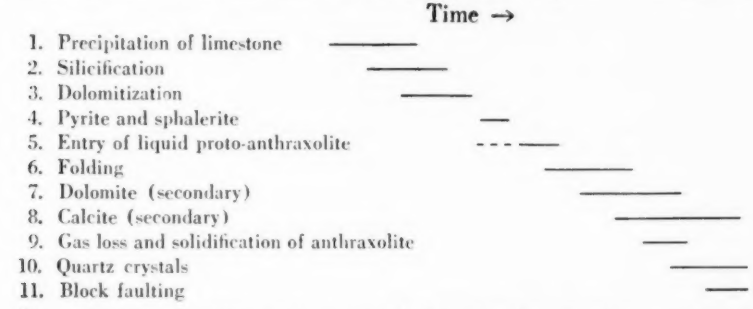
from the same pockets is indistinguishable from the massive variety found elsewhere. Large quantities of anthraxolite from Diamond Hill proved to be so intimately associated with minute crystals of quartz that the difficulty of adequate separation prohibited an accurate determination of the specific gravity. It was concentrated as fully as possible and pulverized, but only a few grains floated in carbon tetrachloride (specific gravity 1.595 at 20°C.). It is therefore presumed that the specific gravity is higher than the anthraxolite from other localities. Due to the difficulty of concentration, the Diamond Hill anthraxolite was not chemically analyzed.

The massive anthraxolite of the Mohawk Valley is of remarkably constant composition as shown by the two ultimate analyses. The material from Flat Creek has a specific gravity of 1.37; that at Salisbury, 1.39. The specific gravity of the Diamond Hill material may approach that of the U.S.S.R. material (Schungite) which is 1.84.

The aforementioned analyses are characteristic of anthraxolites and, aside from ash, typify anthracite coals in general. The high carbon content, together with the approximate 1:1 hydrogen to oxygen ratio are the diagnostic characteristics. The grains which coke when heated and the soft substance coating the pockets at Little Falls are probably lower in carbon and higher in volatiles than the massive anthraxolite; the disseminated anthraxolite from Diamond Hill may conceivably be higher in carbon than the average massive anthraxolite.

THE PHYSICO-CHEMICAL ENVIRONMENT

The following postulated sequence of events depicts the physico-chemical conditions which existed during the interval of time in which the primitive substance was altered to anthraxolite. The paragenetic sequence is as follows:



The sequence of entry varies somewhat from place to place, and, as a matter of fact, it is surprising because of its uniformity. Pike (1949) observed dolocasts in chert which would suggest that dolomitization, at least locally, preceded silicification. Conversely, the observed silicified fossils in chert coupled with their absence in the dolomite would imply that cherty limestone preceded cherty dolomite, i.e. silicification antedated dolomitization. Secondary dolomite was deposited prior to secondary calcite where the two occur together and in advance of the solidification of the proto-anthraxolite. The deposition of the quartz crystals and calcite, and the entry of the proto-

anthraxolite overlap considerably. At Diamond Hill the anthraxolite permeates and is found as a crust around clusters of small (1/16-1/32 inch) quartz and dolomite crystals which must have been present before the entry of the bitumen. The entry of the proto-bitumen antedates that of the quartz in all other observed localities, but the "fossil" bubbles of anthraxolite and the "phantom" coatings in some quartz crystals indicate that the primitive substance was liquid and mobile shortly before and synchronous with the deposition of some of the quartz. In the Chuctanunda dolomite the entry and alteration of the bitumen postdates the deposition of calcite as shown by the crusts of anthraxolite on calcite crystals. In contrast, in the Little Falls dolomite the calcite crosscuts or overlies the anthraxolite suggesting deposition after the final polymerization of the anthraxolite.

Following are the physico-chemical conditions which existed during the changes in the anthraxolite:

1. The primitive carbonaceous substance was a liquid as shown by its position in the lower portion of the pockets (it has a lower specific gravity than quartz or calcite) and by the bubble pits and spheroids which must have formed in a viscous mass.

2. The presence of an aqueous fluid before, during, and after the solidification of the proto-anthraxolite is demonstrated by the overlapping of the deposition of quartz and calcite with the entry and alteration of proto-anthraxolite. Presumably, however, the anthraxolite saturated the rock at some period.

3. A temperate environment probably existed during the changes. Evidence supporting this is the absence of any high temperature minerals and the lack of recrystallization of the dolomitic rocks. Furthermore, no intrusive rocks were noted at or near any of the exposures. Using a bubble-filling technique, Dr. F. G. Smith of the University of Toronto obtained a temperature of formation of $51°\pm2°$C. for one quartz crystal.

Using an average temperature gradient of 1°F. for 60 feet together with the temperature of formation of $51°\pm2°$C. (120°F. to 127°F.) and assuming an average surface temperature of 70°F., we arrive at the interesting disclosure that the dolomites had 3000 to 3500 feet of sedimentary cover when the quartz crystals were forming. Computing the average thickness of sedimentary strata which presumably covered the Mohawk Valley would indicate that the quartz crystallization and anthraxolite solidification took place not earlier than post-Queenston time and possibly as late as Onondaga time. The upper limit is less predictable since it is doubtful just how much, if any, of the Middle Silurian (Clintonian) sediments extended as far as the Mohawk Valley region.

The time of formation of anthraxolite can be further restricted. Field criteria illustrate that block faulting postdated the formation of the anthraxolite. The normal faulting may be as late as Lockport time. This would confine the period of anthraxolite formation to post-Queenston and pre-Lockport time. Either Medinan or Clintonian time appears as close an approximation for the anthraxolite formation as is now possible.

4. Pressure could never have been very high. As the pockets in which alteration took place were partly filled with proto-anthraxolite, the maximum pressure must have been approximately that of a hydrostatic head of a column of water a few thousand feet high, i.e. the maximum thickness of sedimentary cover. Smith[1] reports, "One large inclusion was removed as ice after it split the crystal. It effervesced slightly on melting, and a color indicator showed a pH near 8." Effervescence of the removed inclusion signifies a higher than atmospheric pressure at the time of formation of the crystal.

5. The aqueous fluid present during the changes was probably saturated in Ca^{++}, Mg^{++}, CO_3^{--} (and HCO_3^- and H_2CO_3), SiO_2, and possibly O_2 and N_2. The ions OH^- and H^+ were also available for possible chemical reactions. Normal constituents of sea water were certainly in contact with the proto-anthraxolite at some stages. It is probable that the aqueous solution was stationary and that quartz and calcite crystallization were produced by a diffusion process. Evidence supporting this is the depth of probable change (3000 to 3500 feet) eliminating the possibility of circulating ground water. Additional evidence is the physical and chemical uniformity of the massive anthraxolite which denotes a constant set of conditions existent over a wide area. Moving hydrothermal or vadose waters would tend to follow avenues of greater permeability, thus becoming concentrated and producing non-uniform results.

It is possible that the original substance was petroliferous or asphaltic. In order to determine the feasibility of such a material being the primitive substance, it is necessary to investigate some of the possible reactions from a thermodynamic viewpoint. The nature of the free energy offers an indication of the likelihood of a given reaction occurring, for the reaction with the lowest free energy is the most likely to occur, other factors being constant.

In the following possible reactions the original material is assumed to be decane, but as can be seen below, the hydrocarbon selected is not a critical factor as it is a constant in each equation, and therefore the relative free energies are unaffected.

	Equation	ΔF in cal/mol 298° K
1.	$C_{10}H_{22} + 15\frac{1}{2}\ O_2 \rightarrow 10CO_2 + 11\ H_2O$	−1,568,330
2.	$C_{10}H_{22} + 10\frac{1}{2}\ O_2 \rightarrow 10CO + 11\ H_2O$	− 950,830
3.	$C_{10}H_{22} + 5\frac{1}{2}\ O_2 \rightarrow 10\ C + 11\ H_2O$	− 625,730
4.	$C_{10}H_{22} + 22\ OH^- \rightarrow 10\ C + 22\ H_2O$	− 423,880
5.	$C_{10}H_{22} + 22\ CO_3^{--} \rightarrow 10\ C + 22\ HCO_3^-$	− 316,850
6.	$C_{10}H_{22} + 11\ CO_3^{--} \rightarrow 10\ C + 11\ CO_2 + 11\ H_2O$	− 279,230
7.	$C_{10}H_{22} + 7\frac{1}{3}\ N_2 \rightarrow 10\ C + 7\frac{1}{3}\ NH_3$	− 32,243
8.	$C_{10}H_{22} \rightarrow 10\ C + 11\ H_2$	− 3,570

Reactions 1, 2, and 3, the formations of CO_2, CO, and C, are the most probable according to the thermodynamic data. However, the presence of unoxidized pyrite is difficult to explain if free oxygen were available. Furthermore, the present volumes of the anthraxolite (about 50 percent of the former volume at Flat Creek) suggest that neither reaction 1 nor 2 could have been of major importance. The present volume is essentially what would be expected

[1] Letter of October 30, 1953.

if the hydrogen alone were removed and carbon remained. It seems clear that very little carbon was lost in the reactions.

Reactions 4, 5 and 6 are considerably less likely to occur if oxygen were present. However, if oxygen were absent these reactions become distinct possibilities. A problem arises in that if oxygen were not present and the initial substance consisted only of carbon and hydrogen it is difficult to explain the oxygen content of the anthraxolite!

Reactions 7 and 8 are extremely unlikely on the basis of their high free energies.

HYPOTHESIS OF ORIGIN AND CONCLUSIONS

The chemical analyses previously listed indicate a strong similarity to analogous substances occurring in Canada and the U.S.S.R. Asphaltic bitumens, as grahamite and gilsonite, either contain no oxygen or have a high hydrogen-oxygen ratio. The hydrogen-oxygen ratio of about 1:1 in anthraxolite is typical of anthracite coal but not what is expected in an asphaltic bitumen.

On the basis of thermodynamic and chemical reasoning it seems improbable that the anthraxolite ever had the composition of any of the known asphaltic substances, i.e. ever had a high hydrogen-oxygen ratio. The lineage more likely followed that of coal, starting with a higher percentage of oxygen than hydrogen by weight and progressing to an approximate 1:1 ratio as the rank increased. It is significant that if it were an asphaltic bitumen, at some stage it would have been lighter than water. Since it would be viscous at this time, it would have a tendency to adhere to the upper part of the vug. This is not borne out by the field evidence.

The changes may be similar to the process of fusinization, i.e. the low temperature-low pressure carbonization of some components of wood. According to Schopf (1949) and Miller (1949), most fusinization occurs while the woody material is in the peat stage and affects the cellulose or lignocellulosic components in the wood. Metamorphism is apparently not necessary for fusinization. Changes of this type have been synthesized in the laboratory. Berl (1934, 1935) was able to produce coal of bituminous rank by heating cellulose and other carbohydrates in a weakly alkaline solution at temperatures as low as 230°C. The substances altered first to a viscous, black material similar to asphalt and then, with further heating, to coal. The alkalinity was derived from the presence of such minerals as calcite, dolomite, magnesite and zeolites.

Substituting time for temperature, and a vegetable material of unknown composition for known (the only abundant organic remains in the anthraxolite-bearing strata are the *Cryptozoon* reefs and biostromes) the conditions during the Lower Paleozoic in the Mohawk Valley may well have been duplicated by Berl's experiments so as to create anthraxolite.

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COMMUNICATIONS

NOTE ON THE RELATIVE ABUNDANCE OF SOME TRACE ELEMENTS NEAR THE LOWER AND UPPER CONTACTS OF THE PALISADES SILL

GERALD M. FRIEDMAN

The author is currently studying the differentiation of the Mamainse diabase in the Canadian shield. This Precambrian diabase mass has been greatly altered by hydrothermal action. As chemical analyses are expensive, and as the composition of pyroxenes and feldspars cannot be determined locally because of extreme alteration, it was thought that trace elements might provide a tool for studying differentiation trends. Recent papers by Wager and Mitchell (1950, 1951) have indicated a parallelism between the fractionation trends of basaltic magma and the relative abundance of certain trace elements in the differentiated rocks.

Before applying the trace element method to the Mamainse diabase, it was decided to test it at the Palisades, the petrology of which is known in detail. As it was planned to use a minimum number of analyses, samples were taken from near the lower and upper contacts. The author does not intend to make a further study of the Palisades, and the results of the analyses are therefore put on record at this stage.

The petrology of the Palisades diabase has been studied in detail by Walker (1940) and no need is seen to recapitulate what has been said before. The following trends stand out (table 1): Comparison of the relative abundance of the trace elements at lower and upper contacts indicates a decrease in Cr, Co, Cu, Mn, Ti(?), and V toward the top. Nickel apparently shows little differentiation. Wet chemical analyses of samples taken at 48 and 92 feet above the contact gave respectively 0.049 and 0.055 percent nickel. There may be a decrease in nickel from the contact upwards and an increase nearer the top, but more data are needed to test this point.

Table 1

	1 ft. above contact	3 ft. above contact	9 ft. above contact	Upper contact
B_2O_3	.001–.01%	.005–.05%	.001–.01%	.03–.3%
Cr_2O_3	.01–.1	.01–.1	.01–.1	.005–.05
CoO	.002–.02	.002–.02	.002–.02	.001–.01
CuO	.001–.01	.001–.01	.001–.01	$<$.001
MnO	.02–.2	.02–2.	.02–2.	.01–.1
NiO	.005–.05	.005–.05	.003–.03	.005–.05
TiO_2	.2–2.	.2–2.	.02–.2	.03–3.
V_2O_5	.005–.05	.005–.05	.005–.05	.001–.01

An enrichment of boron was noted near the upper contact. Fairbairn, Ahrens and Gorfinkle (1953) do not mention boron in the diabases of Ontario. Previous investigators, it appears, have not tested the relative distribution of boron in the process of fractionation of a basaltic magma. The obser-

vation made at the Palisades would indicate an enrichment in volatiles near the top of basic sills.

The samples from the lower contact were taken at Fort Lee, New Jersey, near the George Washington Bridge. The specimen from the upper contact was sampled near the Englewood Golf Club. The two samples for nickel analyses were taken at Edgewater, N. J.

Gratitude is expressed to Drs. J. Berman and P. M. Ambrose for the spectrographic analyses and to Mr. Jack Moody and the late E. H. Sarles for the nickel analyses.

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TERTIARY STRATIGRAPHY OF THE FAR EAST A PROTEST

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At the end of a lifetime's study of the Tertiary strata of the East Indies, K. Martin published a condensed review of his work (1919). One of his conclusions was that the Tertiary mollusk species of the Far East, without exception, are different from those in the basin of Paris and elsewhere in Europe, although a superficial resemblance is to be recognized. Martin showed that an open-sea connection cannot possibly have existed between Europe and the Far East, at least not since the Upper Eocene. Apparently marine faunas of both areas developed independently as autochthonous associations. Under such circumstances the use of European stratigraphic names for East Indian strata had no significance. A regional system of stratigraphy seemed the only plausible solution. Such a system, indicating the sequence of stratigraphic units by a letter system, was developed by Dr. I. M. Van der Vlerk as early as 1925. Soon afterward it was followed by an official printed communication (Van der Vlerk, and Umbgrove, 1927). After being revised and

elaborated (Leupold and Van der Vlerk, 1931), it appeared to be extremely successful. Its practical usefulness was appreciated not only in the East Indies but also in other Tertiary districts of the Far East in an area extending from the east coast of Africa as far as the Philippines and Japan, and thence southward to New Zealand, including such areas as the Fijis, Samoa, and New Caledonia.

The present author always felt it a great privilege to follow at close hand Van der Vlerk's endeavor in developing his system, and is glad to say that he stimulated the work and occasionally participated in its elaboration, for example, when illustrating the little joint handbook "Tertiaire gidsforaminiferen" (Tertiary index-foraminifera).

It is therefore unfortunate that in at least one case (Wirjodihardjo, 1952) this letter classification has been referred to without mentioning the original source and in another case has been credited to another person (Ikebe, in Takai, 1953).

This short communication is an appeal to all scientists in general, and students of Tertiary stratigraphy in particular, to keep strictly to the methods of correctness in giving the credit to the actual founder of the letter classification of the Tertiary of the Far East. Not mentioning the original source, and even simply mentioning another man's work as if it were a new product of a third person is a cleancut case of plagiary. In this respect my discussion stands as an expression of condemnation and protest.

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REVIEWS

Will Quantum Physics Remain Indeterministic?; by LOUIS DE BROGLIE. P. 71. Paris, 1953 (Gauthier-Villars, 1500 francs, paper cover).—De Broglie's interest in a deterministic interpretation of quantum mechanics has been revived by the publications of David Bohm. This booklet serves to draw attention to the author's earlier writings, some of which (having originally appeared between 1924 and 1927) are reproduced. Of the two theories previously proposed (the pilot-wave theory and the double-solution theory) the first is regarded as untenable, the latter as promising. Objections raised against the pilot-wave interpretation are the following:

1. Electrons in s–states are at rest.
2. Particles can attain speeds greater than that of light.
3. The Ψ–function cannot represent physical reality because it collapses into a δ–function with infinite suddenness when a position measurement is made.
4. The Ψ–wave is a many-dimensional construct, not a three-dimensional wave, and is therefore a very curious physical entity.

It seems fair to say that some of these objections have been removed by the work of Bohm.

The book contains an exposition of the double-solution theory and its difficulties. It ends with an interesting attempt by J. P. Vigier, a collaborator of the author, to connect this theory with general relativity.

HENRY MARGENAU

Petrography, An Introduction to the Study of Rocks in Thin Sections; by HOWEL WILLIAMS, F. J. TURNER, and C. M. GILBERT. P. x, 406; 133 figs. San Francisco, 1954 (W. H. Freeman and Company, $6.50).—The responsibility for authorship of *Petrography* is as follows: Part I, *Igneous Rocks* (157 pages)—Williams; Part II, *Metamorphic Rocks* (87 pages)—Turner; Part III, *Sedimentary Rocks* (134 pages)—Gilbert. Each part of this book lives up to the promise of the preface to be more concerned with the *description* of rocks than with problems of genesis. The only comparable book in English is Alfred Harker's *Petrology for Students*, originally published in 1895, with a seventh edition in 1935. In this well-known text 205 pages are devoted to igneous rocks, 33 pages to metamorphic rocks, and 56 pages to sedimentary rocks. Comparison of the two books shows that petrographic developments of the past 59 years are reflected in the new American text largely by a very greatly expanded description of sedimentary rocks and the discussion of the metamorphic rocks in the light of the principles of the physico-chemical facies classification. The hypothesis of fractional crystallization as a major factor in the diversification of igneous rocks was developed during this period but has had little influence on their classification or petrography. Harker's book contains 185 drawings of thin sections of rocks, where-

as *Petrography* contains 361. Here too, the difference is largely in an increased number of illustrations of the sedimentary and metamorphic rocks.

Part I, on igneous rocks, is a thorough, dependable, up-to-date, well-illustrated text, containing descriptions of more than 150 varieties. In addition to the major types, there are many which will challenge the student's geographical and linguistic knowledge, such as arsoite, ciminite, jacupirangite, kaiwekite, madupite, malignite, solvsbergite, and wolgidite, to mention only a few. Although many of these names are not necessary in an *introduction* to rocks, the precedent was set by Harker's book. Perhaps part of the curse for the student may be mitigated by the fact that none of them is used in the headings or subheadings; they only appear in italics in the text for easy reference and do serve as a lexicon that will aid the reading of petrographic literature.

Some inconsistencies in usage were noted. On page 10 deuteric minerals are defined in terms of secondary *alteration* and on page 23 mineral *fillings* of amygdules are termed deuteric. Again on page 32 a sentence starts "And, since most *medium-grained* rocks, such as *micro*granites," yet the next sentence states that *fine-grained* facies (elsewhere defined as less than 1 mm) can be qualified by the use of the prefix *micro*.

Part II on metamorphic rocks contains really excellent summaries of their petrogeny. The chapter headings are Hornfelses and Spotted Slates; Cataclasites, Mylonites and Phyllonites; Slates, Phyllites, and Schists; Amphibolites, Granulites and Eclogites. A table showing the mineralogical varieties is given for each appropriate group. Such *moderate* temperature rocks as the albite-epidote-amphibolite facies are described with the *low-grade* schists. The coverage of the various varieties of rocks is extensive.

The author has taken a position on the use of the term gneiss that not only is of doubtful wisdom but will cause the student much confusion in the use of geologic literature. On page 174 gneiss is described as a coarse-grained irregularly banded metamorphic rock with a poorly defined schistosity because of the preponderance of quartz and feldspar over micaceous minerals. On page 236, however, it is stated that "there has been some objection to the use of the term 'gneiss' for rocks not of plutonic igneous origin. For this reason we use 'quartzo-feldspathic schist' to cover schists rich in quartz and feldspar within the amphibolite facies." The result is that there is no section on "gneisses" and the student will search in vain for any description under the terms, granite gneiss or syenite gneiss, etc. Augen gneisses, however, are described as such in the chapter on cataclasites, mylonites, and phyllonites. Such old standby words as hornstone, soapstone, steatite, tactite, and quartzite do not appear in the index. Rocks of "mixed" origin which characterize so much of large areas of high grade regional metamorphism in the world deserve more intensive treatment.

Part III, Sedimentary Rocks: Compared with other American texts that deal with sedimentary rocks, this one is notable for the way the material has been synthesized and the clarity with which it has been presented.

The classification used for sedimentary rocks is based on the concept of two genetic end members, one detrital or allogenic, the other chemical or authigenic.

In the brief first chapter on the origin of sedimentary rocks, the discussion of the most fundamental factor, the tectonic environment, is much too brief and general to serve as a guide to any real understanding of the subject. In the second, on composition and texture, it is disappointing to find no description or thin section drawings of the significant textural feature, *bedding*, which is badly in need of careful study. The omission is the more unfortunate because bedding is so easily observed in thin sections.

Sandstones, the topic of chapter 3, are defined rather unconventionally as including not only rocks composed mainly of sand-sized grains but also those rocks composed mainly of coarse silt-sized grains. This definition is particularly perplexing, for in an earlier discussion of the clastic grade-scale the reader learns that a consolidated aggregate composed mainly of sand-sized grains is a sandstone and one in which most particles are smaller than sand but coarser than clay is a siltstone. Furthermore, silt is not subdivided into coarse and fine grades in the accompanying scale, so the reader has no idea what lower size limit Gilbert does assign his sandstone group. The advantage of this modified definition is not apparent, nor is it discussed.

Two types of sandstone are defined by their degree of sorting: one is the relatively well-sorted *arenite* with less than 10 percent matrix, the other the poorly sorted *wacke* with more than 10 percent matrix. These two basic groups are then subdivided on the basis of relative content of stable and unstable constituents. Two triangular diagrams illustrate the limits and interrelationships of the wackes and arenites. Despite the unwelcome addition of two more names for sandstone types, this classification expresses more clearly than any other yet proposed the basic relationships of texture and composition in the makeup of detrital sedimentary rocks. Many readers will regret that there is only one illustration of sandstone from the Paleozoic sequence of the Appalachian geosyncline and the Mesozoic deposits of the Rocky Mountain geosyncline.

Gilbert claims that along the Gulf Coast of the United States and in the ranges along the Pacific Coast there are many less indurated wackes with a general composition similar to that of the lower Paleozoic graywacke of Wales, southern Scotland, and Newfoundland, and of the Mesozoic Franciscan graywackes of California. Actually, there are few, if any, rocks of such composition along the Gulf Coast. Instead, as Gilbert points out on a later page, lithic arenites with less than 10 percent matrix are numerous among the Tertiary strata of that area.

Well-sorted quartz-rich rocks are named quartz arenites, with the reminder that quartzite should not be used for sedimentary rocks because in America it clearly is a metamorphic rock name. For the same reason the term orthoquartzite is not recommended. Yet, rather ironically, quartzite is not mentioned in Part II, Metamorphic Rocks. Chapter 3 concludes with

a good discussion of Authigenic Cement in Sandstones and its sequence of deposition. It is pertinent to note that the results of the important diagenetic processes of authigenesis, intrastratal solution, and cementation which can be studied best in thin section have not been adequately described and illustrated in any American text. It must be added, however, that Gilbert's treatment of this subject is the best available.

Chapter 4, entitled Argillaceous Rocks, is a very brief discussion—7 pages in contrast to 35 pages devoted to sandstones—of those sedimentary rocks composed mainly of fine silt- and clay-sized particle. Because of the unorthodox size limits assigned to sandstone and argillaceous rocks, several common names, such as mudstone and shale, are necessarily given new size limits in this book. The too brief discussion of petrography, with but two drawings of thin sections, could profitably have been expanded to include description and illustrations of different kinds of bedding in very fine-grained detrital rocks, such as the non-glacial marine varves described by Bradley more than twenty years ago.

In Chapter 5, the discussion of Calcareous Rocks is primarily concerned with the classification and description of limestones and a description of the textures of dolomites and dolomitic limestones and the relation of these textures to the processes of dolomitization.

The final chapter, Miscellaneous Sedimentary Rocks, is more precisely a review of additional *chemical* sedimentary rocks. Here the student is introduced to the petrographic descriptions and some problems concerning the origin of siliceous, iron-rich, and phosphatic sediments [sedimentary rocks], and of anhydrite and gypsum. In a book of such thorough coverage, a description of chert associated with products of submarine volcanic activity and of the ferruginous formations of the Lake Superior type would be appropriate.

In the preface the authors state that they have assumed that the student has already learned how to identify rocks by means of the hand lens and is acquainted with the principles of optical mineralogy. The reviewers suggest that *Petrography* can be used almost as well by students of thin section petrography who have not had hand specimen petrography. On the other hand, the nature of the material included and the clarity of the text and illustrations suggest that the book could also be used effectively as a text for hand specimen petrography. The drawings of thin sections would serve as a great aid in understanding the details seen with a hand lens.

Petrography, the first of its kind for North America, is an outstanding and most welcome text. It should play an important part in interesting young geologists in a careful study of rocks and in acquiring a knowledge of them.

A. F. BUDDINGTON
FRANKLYN B. VAN HOUTEN

Geology of the Pearland Quadrangle, California; by LEVI F. NOBLE. U. S. Geol. Survey Geologic Quadrangle Map. Washington, 1953 (2 sheets, $1.00).—This is the first of the Survey's new publication series for California. The 6-minute quadrangle lies north of and just over the San Gabriel Mountains from Los Angeles. The colored geologic map, two sections, and explanation with concise descriptions of the rock units, comprise one sheet. The other sheet includes a text on regional geologic features, the San Andreas fault and fault zone, interpretations of San Andreas history, tectonic and topographic map illustrations, a stratigraphic table, and several large-scale sections by Philip B. King.

Because the San Andreas is well exposed across the quadrangle and because Noble has literally lived in and worked this and adjacent segments of the San Andreas zone over a period of 40 years, it is not surprising that the report is an outstanding contribution to the understanding of this great fault.

The rocks of the Pearland Quadrangle comprise approximately 350 feet of Quaternary, and 3500 feet of Tertiary continental strata, including three newly named formations, lying on Mesozoic granitic and older crystalline basement. The sediments occur principally in or near the San Andreas fault zone. All these rocks have suffered intense, repeated, and recent deformations as evidenced by faulted, folded, and crushed basement rocks; by faulted and sharply folded sedimentary formations, which are usually separated by prominent angular unconformities; and by faulted and folded Recent sediments and topographic surfaces.

Noble emphasizes an important distinction between the San Andreas *fault zone* and the San Andreas *fault*. Here the fault zone is described as a one-mile wide, relatively depressed, faulted and folded belt trending N 63° W. The largest of the mapped and named faults are parallel to the zone trend and most of the many others are at least sub-parallel to it. The San Andreas fault is mapped along the approximate center of the fault zone; the fault is marked by a continuous, straight and narrow, alluviated *fault trench;* and it is bounded on the north by a nearly continuous *fault ridge* (a composite of short and narrow, eastward-trending, en echelon anticlines and faults). The San Andreas fault is the major fault of the San Andreas zone; it is also the fault of most recent activity. (This coincidence of recent trace and major fault may not be true for some other segments of the San Andreas zone.)

Noble carefully describes and interprets the nature of movements on the San Andreas fault, starting from the latest, as follows: (1) scarplet in present stream valley alluvium was, perhaps, formed at the time of the Fort Tejon earthquake of 1857; (2) fault trench and fault ridge topography result from Recent fault movements; (3) drainage line offsets indicate strike-slip (right lateral) displacements to a distance of 4000 feet; (4) a match of an older alluvial facies suggests cumulative right lateral displacement of about 2 miles; (5) sharp unconformities between folded and faulted Pleistocene formations indicate earlier fault zone activity; (6) one Pleistocene formation occurs in two facies in contact along the fault, thus indicating strike-slip displacement totaling several miles; (7) a 1400-foot Tertiary

formation occurs only north of the fault and a 1600-foot Tertiary formation occurs only south of the fault, perhaps due to many miles of strike-slip displacement on the San Andreas, over a very long period of time.

Noble's lucid presentation of geologic facts and ideas is apt to have an important bearing on the solution of San Andreas problems; what is the San Andreas—how old is it—what has been the sense of movement on it—and what is the magmnitude of cumulative displacement? Current diverse interpretations (Hill and Dibblee, 1953; Taliaferro, 1943) are likely to be reconciled by work of this character.

In this reviewer's opinion it is unfortunate that the colors on the map and sections do not all conform; the unlike crystalline rock facies on opposite sides of the fault are not in different colors; type localities of the newly named faults are not described; and the difference between *separation* and *slip* is not always made clear. It is also the reviewer's opinion that a great many miles of right lateral slip is a better explanation for the juxtaposition of unlike basement facies than the explanation of the fault choosing this contact for its location. However, none of these criticisms detracts in any material respect from an important job well done. Fortunately, for those of us who are interested in the San Andreas, we can expect the early publication by the Geological Survey of Noble's nearby Valyermo Quadrangle.

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MASON L. HILL

Carte géologique de la Nouvelle-Calédonie (1:100,000). Sheet 1, Arama-Poum; Map by P. Routhier and A. Arnould, Explanatory Notice (21 p.) by P. Routher. Paris, 1953 (Office de la Recherche Scientifique Outre-Mer, 20, rue Monsieur, Paris, 7e, 1200 francs (appr. $3.50)).—This sheet is the first of 10 planned to present a complete geologic map of New Caledonia, on the basis of surveys begun in 1946. The explanatory notice includes brief descriptions of the rock units mapped, and of the tectonics, geologic history, and mineral deposits. More detailed monographs on the geology of New Caledonia have been or will shortly be published in the Memoirs of the Geological Society of France.

JOHN RODGERS

Morphological Analysis of Land Forms: A Contribution to Physical Geology; by Walther Penck, translated by Hella Czech and Katherine C. Boswell. P. xiv, 429; 18 figs., 12 pls. New York, 1953 (St. Martin's Press, $8.00).—There should be no need to plead the general importance of Walther Penck's *Morphologische Analyze*, a work which has, in this country, successively prompted a sharp critique by Davis, a retrospective symposium by the Association of American Geographers, and a separate chapter in a current textbook. Nor is this the place for an extended reappraisal of Penck's very real contributions to general geomorphology. It is entirely appropriate to express our gratitude for the presentation of a translation of this important work into English.

The translation is, so far as possible, faithful to the original. Thus, readability and even clarity have been deliberately sacrificed in an attempt to present objectively Penck's mature reflections on landscape development. The general barrier imposed by language is down, but the not inconsiderable barrier of personal style remains. A direct acquaintance with Penck's views is still not easy, but the difficulties are due to Penck and not to the language in which he happened to write. Substantial assistance is provided to the reader by glossaries, showing the correspondence, as used in the translation, between some German and English technical terms, many of them originally used by Penck, and by brief summaries of the individual sections. The latter are rightly intended as guide posts. They by no means remove the necessity of traveling the sometimes difficult roads so marked.

Penck's most stimulating arguments concern the genetic significance of slope form and of nick points in stream courses and interfluve profiles. It is thirty years since they were originally published, but it must be conceded that we have reached consensus of opinion in neither case. The arguments of Penck are still pertinent. However faulty in details, they will certainly enter the final, synthetic discussion of either topic. We are therefore deeply indebted to those whose devotion has made it possible to read Penck, rather than about Penck, in English.

CHARLES E. STEARNS

The Medusae of the British Isles. Anthomedusae, Leptomedusae, Limnomedusae, Trachymedusae and Narcomedusae; by F. S. Russell. P. xiii, 530; 319 figs., 35 pls. New York. 1954 (Cambridge University Press, $22.50). —This magnificent monograph represents the completion of over half a century of work started by the late E. T. Browne and continued by the present Director of the Laboratory of the Marine Biological Association at Plymouth. After brief anatomical and biological chapters on the group, the bulk of the work is occupied with a detailed description of approximately ninety species of hydrozoan medusae known from British waters. The species considered constitute about three-quarters of the fauna of the northeastern Atlantic, and many are distributed very widely. The book, therefore, has a utility far beyond the British fauna. It is richly illustrated, most species appearing as in life, and often in color, on the plates, in a diagrammatic pictorial key, and also in drawings showing the rather disappointing appearance of preserved specimens in plankton samples. The nomenclature of the medusae still has to be maintained independent of that of the hydroids, so that no biologically satisfactory classification is yet possible, but Russell, in spite of his disappointment at not being able to achieve a rational taxonomy, has made a number of advances towards that end. In his treatment of some classificatory problems it is occasionally difficult to ascertain exactly what innovations are being introduced, but this is the only criticism of his treatment that the present reviewer can make. It is evident that a number of problems relating to variation and intraspecific taxonomy remain; their solution will be enormously facilitated by this work. American workers on freshwater biology will find an unexpected and most useful feature in an extended special bibliography

of publications on the freshwater jelly-fish *Craspedacusta*. The book is in general one of the finest taxonomic monographs published in recent years and has a long life ahead as a standard work.

G. E. HUTCHINSON

Pulications Recently Received

U. S. Geological Survey Bulletins as follows: 982-G, Geology of the Dover Magnetite District, Morris County, New Jersey; by P. K. Sims. 995-D, Geologic Investigation of the Boyertown Magnetite Deposits in Pennsylvania; by H. E. Hawkes, Helmuth Wedow, and R. J. Balsley ($ .50). 997, The Geology and Ore Deposits of the Reese River District, Lander County, Nevada; by C. P. Ross ($1.75). 1002-D, Geophysical Abstracts, October-December 1953 (Nos. 14805-15026); by M. C. Rabbitt, S. T. Vesselowsky and others ($ .25). 1006, Collected Papers on Methods of Analysis for Uranium and Thorium; compiled by F. S. Grimaldi, Irving May, M. H. Fletcher, and Jane Titcomb ($1.00). Washington, 1953, 1954.

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